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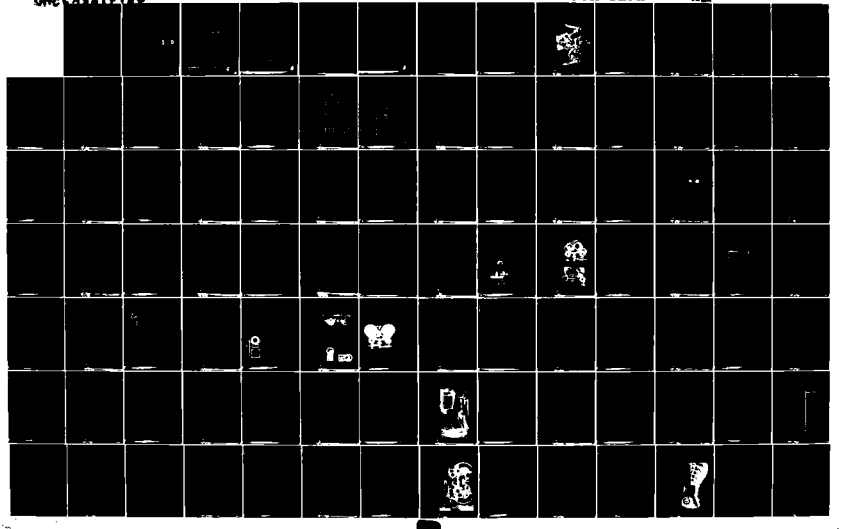

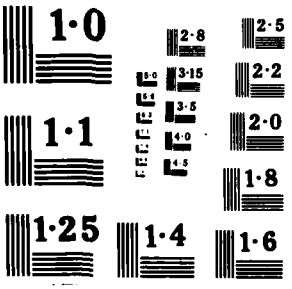

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COMPUTER-ASSISTED EYE EXAMINATION

Background and Prospects

Elwin Marg

With contributions from

Arthur G. Bennett
Maxwell M. Lang
Robert D. Reinecke

San Francisco Press, Inc.

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This volume is dedicated
to my wife

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PREFACE

There are times when some of us yearn for the simpler life of yesteryear. We have a nostalgic feeling for simple and direct responses to what appear to be simple and direct problems. In the health field, the skilled doctor may give, in the form of a prescription, what seems to be a basic answer to a problem. Yet when this thought process is organized into a flow chart, the apparent simplicity may prove to be deceptive. Much potential complexity has been tacitly rejected in a subconscious reasoning process. In order to answer a simple problem with confidence, many alternate factors or solutions must be eliminated; much of this reasoning may be below the conscious level. Even so, the problem may still turn out to be more complex in itself than meets the eye.

We are biologically highly complicated. We are impatient for effective answers and too economically minded to want to turn back the clock. As time moves inexorably on we must search for new ways to become more efficient and effective with our skills and resources.

The computer has the potential of giving individual attention to patient needs without the high cost of human service. We must adapt it to perform with skill and economy but leave the patient a feeling of dignity. That characterizes the goal for automation in eye examinations.

For the foreseeable future we shall speak of computer-*assisted* eye examination because the computer has not yet been developed to the point where it can stand alone. Nevertheless, computer assistance holds the promise of greater access of eye examinations and lower cost. The beginning has been made. It is hoped that others will join and continue to develop this field of man-machine interaction for the visual health of mankind.

*

The work reported in this volume is obviously too extensive to be that of one person alone. The original concept arose in 1965 during the preparation of lectures for a course on advanced geometrical optics as studied with a high-level computer language, FORTRAN. In the course of this preparation it became obvious that eye refractions could in principle be accomplished by computers. There were two primary conceptual problems. First was that of communication between the computer and the patient. The computer could speak to the patient only in prearranged messages of limited duration, and the patient could speak to the computer with a pushbutton answer box. The second problem was that of determining the visual acuity. The answer to that came while I was undergoing a physical examination by means of von Bekesy's audiometer. His concepts could be adapted, with some modifications, to visual acuity.

The method was tried with the help of Gary Liberman, then an undergraduate optometry student at the University. Following him, many student collaborators have worked on the project. Among those who were optometry students at the time were Donald Dilly, William Baron, Robert Wakamatsu, Rebecca Ng, William Wong, Curtis W. Keswick, Richard C. Koleszar, Lisa E. Moon, Roy L. Baker, and Khin P. Chung. Glen L. McCormack was a graduate student in physiological optics at the time.

A number of computer scientists who were graduate engineering students at the time have contributed to the project. They include Paul Chang, Steven Greenfield, Allen N. Weiner, John Cosley, Yuji Yamasaki, George Hung, Brian J. Phillips, Edward C. Ng, Simon M. Favre, Pavel Stoffel, Peter D. Robertson, and L. Jefferson Braswell.

C.A. Laudel did the machining for Refractors II and III following the initial mechanical design of Edward Chan. Lens specifications for Refractor III were drawn by Dr. Maxwell M. Lang, who also contributed Chapter 3 of this volume.

In some of the earlier phases of this work there was collaboration with Professor E. R. F. W. Crossman, and his graduate student, Peter J. Goodeve.

The most important single collaborator of all has been Dr. Chacko C. Neroth. His extraordinary ability extends well beyond electrical engineering and computer science. His interest

and good humor made our group meetings both pleasant and productive. Without him this project would not have reached its present state of fruition.

On the administrative and literary side there have been a number of efficient collaborators including Nancy I. Uyemura, June Kress, Mary Jane Macdwyer, Gail Sheridan, Cynthia Bass and Donald C. Hunter. Eileen Glenn and Linda Keul, working as editorial assistants, compiled the various chapters, appendixes, and illustrations into coherent organization. Eileen Glenn also phototypeset the text.

Plates were drawn by Tamia Marg, with the exception of Plate A.

The earlier stages of this project were supported by a grant from the National Institutes of Health. Its current fruition was made possible by a contract from the U.S. Army Medical Research and Development Command. The contract monitors who were most helpful in expediting the various administrative aspects of the work were LTC John Snell, Major Frank Kovach Jr. and Col. James Sampson. Interest and support were gratefully received from successive Chiefs of Optometry of the Surgeon General's Office, Col. Henry Maes, LTC Gene Borland, and Col. Arthur Giroux. Col. Budd Appleton, formerly the Chief Army Ophthalmologist, has always shown his interest with stimulating questions and comments. Special thanks are also due to Jerome W. Malek, Chief of the General Engineering Branch of the Medical Bioengineering Research and Development Laboratory, who has replaced Col. Sampson as monitor of our project. The collaboration at the Optometry Clinic of the Letterman Army Medical Center at the Presidio in San Francisco was made effective by the active help and cooperation of LTC David E. Johnson, the former chief, and Major Kenneth W. Anderson, the current one.

General intellectual support at the highest level was received from my colleague and friend Professor Lawrence Stark of this University.

To the others who played perhaps somewhat smaller roles in this project I also offer my thanks and gratitude. Those who have contributed directly to this volume are acknowledged in the appropriate place.

My only regret, as I see this book taking form, is that computers have not been developed to the extent where they can find and correct all the errors I have no doubt committed. It may be just as well that this development is not imminent, however, because when they reach that state of perfection they may well be ready to write the book themselves.

•

It seems to me that making the commitment to write a book involves a conflict between one's other interests and obligations, natural laziness, or perhaps conservation of energy, on one hand. On the other hand the creative aspects are stimulating. My primary motivation has been to collect the work amassed on this project into a single, easily referred to, and relatively compact form. My interest in visual neurophysiology would have dominated except for this one consideration. So much effort has gone into devising and testing this project that it seemed important to have the documentation in one central place for reference.

Naturally, I hope it will also be of interest to a somewhat broad readership. It is of value to optometry students who seek an approach to eye examination different from the one to which they are accustomed. It is of interest to health economists to point an alternate pathway in the delivery of eye examinations. It is of interest to electrical and industrial engineers as an unusual application of computer science. Finally, it will be of interest to computers of the future when they are collecting the early history of their once primitive kind.

Elwin Marg

Berkeley, California, 1980

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PLATE A Examination of the eye more than a century ago. From Duke-Elder's *System of Ophthalmology*, Volume 5. Henry Kimpton Ltd., London, 1970, by permission.

Chapter 1
INTRODUCTION

AN EYE EXAMINATION may be organized from a number of specific test procedures to solve a recognized problem or to answer a specific question; or it may be a general one to assess the status of vision and determine whether there are any problems. The former is the province of the specialist in vision; the latter, of the general vision practitioner. It is the general vision practitioner rather than the contact-lens specialist or the eye surgeon who can be aided materially by computers at this time.

A thorough examination always requires many tests, most of which are normal or negative. If the examiner could limit the test to patients who have been screened for greater likelihood of a positive finding on a test or a battery of tests, he would be spending his time much more efficiently.

In principle, a computerized test can be more valid than one administered by a human practitioner. That may one day become true of a basic electrocardiogram (EKG), although computer EKG pattern recognition has not yet reached its definitive state of development. In eye examinations, the practitioner has to fit the results of other diagnostic tests into a complete diagnosis and finally into a treatment; several levels or layers of data from various sources, obtained by various means and instruments, combine and interact to build a picture or model of the patient's status and his possible problems. Next, a course of action is planned on how to meet these problems. With the development of instrumentation, the practitioner has been able to build in his mind a more valid and useful model of the patient's visual system. It is becoming increasingly feasible to make some of our instruments more intelligent so that models can be presented ready made, ultimately via computer graphics, to the practitioner.

In computer-assisted eye examinations the practitioner sees the patient and interacts with him primarily for two reasons: to ascertain that the computer system and program flow charts have been adequate to the task, and to give the patient personal interaction in the examination. More useful information might be obtained from the patient directly by the practitioner, but the quality of the examination and the cost of obtaining these data must be evaluated and taken into account.

Currently the computer system can suggest an optical prescription. There are means by which the system can evaluate its own validity. Nevertheless, the practitioner must remain in control, not only for human contact but also because of the limitations of communication between computer and patient. The patient talks to the computer through a response or answer box. For the case history there are three buttons, *yes, no,* and *doubtful.* The refraction response box has five pushbuttons, four placed in the configuration of the points of a diamond and one in the center. Each of the buttons has several possible meanings, but only one at a time for a given test. In the visual-acuity test each point of the diamond represents the direction of the opening of the broken ring or C, up, down, right, or left. In a choice between two lenses presented sequentially, lens number one is represented as the better choice by the top button, and lens number two by the bottom one. The center button, with an exception to be discussed later, is reserved for calling for a repetition of the instructions.

Patient-computer communication is restricted. The patient is limited in what he can say to the system. He cannot ask questions; he cannot ask for sympathy or approbation during the test. He cannot explain his apparent failure or express doubts. All such human but functionally questionable communications must await the human interview afterwards.

The computer is also limited by the prerecorded messages in what it can say to the patient. There is currently no economical possibility of spontaneous banter or joking, although standard jokes could be programmed much as some classroom lecturers use the same ones year after year.

Philosophical Bases

In human affairs there is generally a striving for change—change for what is believed to be for the better. In the political world it is called reform. In the esthetic world it is exemplified by *art nouveau*. In the business and professional world it is named effectiveness and efficiency. *Effectiveness* indicates that the objective of the task can be met. *Efficiency* is a measure of the relative effort that must be used.

Effective eye examinations have been performed for more than a century. New instruments based on new scientific concepts made them possible. The invention of the ophthalmoscope opened to view the deep interior of the living eye. The retinoscope, or skiascope, gave a stable and reliable estimate of the refractive state of the eye. The trial lens set, and its development into a refractor, offered a systematic and precise choice of refractive-test powers. Additional data could be obtained from the ophthalmometer or keratometer about the curvature that indicates the dioptric power of the refracting surface of the cornea, and from the slit-lamp corneal microscope about the refracting media, especially the crystalline lens and cornea.

These instruments, which characterize modern eye examinations, have all been well established for more than half a century. The last fundamental improvement in them was the replacement of external light sources with internal incandescent lamps. Further improvements have come in very small steps, with many changes being based more on selling points than on examination criteria.

Ophthalmic instrumentation has not developed by itself, but rather from the practical applications of new concepts in technology. Bright and steady light sources had to replace flickering oil lamps and candles. Ground and polished optical surfaces were needed to overcome the defects of blown glass. Tubes, diaphragms, gears, detents, scales, even knurled knobs had to be readily available from the machine-shop lathe before brilliant new ideas such as the ophthalmoscope could be translated into clinical usefulness.

In the past decade a new development of science and technology—the computer—has had a profound effect on industry that is just now reaching ophthalmic instrumentation. Continuation of this trend would seem slow but sure, a judgment based not only on the movement of all technology toward computerization, but on the advantages it can provide in eye examination.

The economic justification is the primary but not the only reason. Ultimately the quality of eye examinations should improve with computerization, although at the current stage of development the goal has been to have the computer do what it can do without any decrease in the quality of the service. Improvements can be sought after the initial development is accomplished and the operation of the system is better understood. Other justifications include more ready access and reduction of language and other cultural barriers. Access is not currently a serious problem, but it could become one if third-party payment for eye examinations and prescriptions should become common, as might happen with the passage of a National Health Act similar to that in the United Kingdom, where the initial increase in demand was tenfold. Any large change is likely to throw the current balance between supply and demand out of comfortable equilibrium.

Aspects of the eye examination not readily computerizable will become more important in the future with the further development of science and technology in our field. For example, the examination of infants before the end of the sensitive or critical period promises to become a vital preventive eye-care service. The detection and diagnosis of diseases may become more important as new treatments are found to prevent or cure them before irreversible damage is

done. The trained personnel for these increased services may well come from among those released from more rote activities by computer systems.

The quest then is to use computers combined with effective ophthalmic instruments, the principles of which have been developed over the past century, to provide a more efficient eye examination—efficient in terms of cost and skill, and no less effective in terms of quality than the current manual ones.

General Eye Examination

An eye examination designed to determine the visual condition of a patient may be divided into the following parts.

1 Entrance Interrogation

This part includes the name, sex, age, address, telephone numbers, occupation, identification number, and billing information.

2 Case History

A patient may present himself because he has a specific complaint in regard to his vision, or he may want an examination to be assured that there is no insidious problem or disease. If the patient answers correctly, the case history yields the reason for the visit. The examination has two primary goals: first, to discover any threat to vision and remove it; and second, to satisfy the patient's complaints, especially the chief complaint. The case history reveals the complaint. Without it the practitioner must assume it from the examination data. Most commonly the problem is poor visual acuity or 'eye strain' because of a correctable refractive error.

3 Visual Acuity

The primary symptom of a need for refractive correction is poor visual acuity. Generally it is also the chief complaint. More than a single visual acuity value is required for each eye. Acuity must be measured with various lenses in addition to an initial measurement of the naked eye. It is also recorded with any previous prescription for distance vision. It may also be measured with the lenses found by objective means such as retinoscopy. After the determination of any increase of lens power for reading, the visual acuity can be measured at the reading distance. However, the initially essential measurements are acuity without glasses and with the most current prescription for distance vision.

4 Examination for Eye Diseases

In a general eye examination this phase can be considered as being a screening examination. A patient having a suspected disease can be referred for a specialized ophthalmological examination. This examination includes observation of the outer eye and adnexia, and the inner eye and fundus by both ophthalmoscopy and slit lamp-corneal microscopy. Field measurements with a tangent screen and tonometry follow.

5 Objective Refraction

Generally an objective refraction—one that does not require any response from the patient—is desirable, but not essential. It gives the examiner confidence in the patient's subjective responses and provides a good starting point for that examination. The classic method for accomplishing the objective refraction is by retinoscopy. Newer methods include automatic retinoscopy and visual evoked potential refraction (Chap. 7).

6 Subjective Refraction

Subjective refraction consists of a battery of tests to provide the combination of lenses that gives maximal visual acuity without activating accommodation. In effect this procedure defines refractive error. No other test has maximum psychophysical visual acuity as its endpoint. It is the heart of the whole eye examination. It provides the best optical prescription that most patients seek. The principle is to determine which of a pair of lenses provides clearer vision and a plus or convex lens bias to inhibit accommodation. It is complicated by the determination of

the power and axis of the cylindrical lens to correct astigmatism. Frequently included in the subjective examination are tests to determine eye motility and balance (heterophoria and duction tests) and, most important, near tests to determine the reading prescription. The latter consists of the distance corrections obtained subjectively plus the nearpoint *addition* or add similarly obtained at the normal reading distance (often taken as 40 cm).

7. Final Decision and Prescription

When the lack of adequate visual acuity is the chief complaint, the maximum visual acuity lens finding from the subjective examination is generally prescribed. If not, an attempt is made to find a solution to the chief complaint from the data obtained.

A computer system can be applied to a general eye examination in the following areas.

1. Entrance Interrogation

These personal data must be entered into the computer manually through a terminal (a teletypewriter connected to a computer), unless they are previously encoded (for example, on a magnetic strip such as those found on credit cards).

2. Case History

A computer can take a case history by limiting the flexibility of communication. The system should be designed so that this limitation is not important to the acquisition of the required data. This goal has been achieved in medicine, including specialized case histories for gynecology and neurology. A general eye-examination case history is different only in that the questions refer to problems of vision. Also, it may be wise to assume that the patient cannot read before obtaining prescription glasses. For this reason (among others) we use an audio format. The questions in a branching program are presented to the patient over a loudspeaker. A response box with three push buttons allows the patient to answer the computer with the messages *yes, no,* or *doubtful.* A *doubtful* response brings a repeat of the question, with a similar response standing for *don't understand,* or *don't know.*[4]

The computer case history is discussed in detail in Chap. 4. It is enough to state at this point that a useful case history for an eye examination can be obtained by a computer system.

3. The Detection and Diagnosis of Disease

Ophthalmoscopy could be automated if computer pattern recognition were of the same level as that of the visual system. Unfortunately, machine pattern recognition is still relatively primitive and it does not seem likely that it will approach that of the human system in the foreseeable future. Ophthalmoscopy seems destined to remain a manual (or visual) art for the present. Similarly, the slit lamp-corneal microscope has the same pattern-recognition requirements and requires perhaps even more manual manipulation to produce the desirable images. Visual fields can be largely automated, although the current costs for the largest systems may need to be reduced for routine testing. Tonometry can be, at least in part, automated. Grolman's noncontact instrument would be the simplest one to use in a computerized facility, since a minimum of manipulation is required and the eye is not touched. However, the main part of screening for disease must be done by highly trained personnel.

4. The Objective Refraction

In ordinary practice the objective refraction is determined by retinoscopy, a method that usually takes a student clinician several years of practice to learn well. Three automated retinoscopes are currently available that can perform essentially the same task without a skilled operator. These devices cost about $20 000 each. Another approach is the use of visual evoked potentials for objective refraction. The simplest substitute for an objective refraction is the prescription of the previous distance correction, if any. Our system has a flow chart that takes the visual acuity through any of these prescriptions or findings available and chooses as the objective-result value the one through which the patient sees the best.

5 *The Subjective Refraction*

The subjective test actually is not a single one but consists of a battery of separate subtests. It can be performed by computer in virtually the same way it is administered by a clinician, with one important modification. The normally unstructured exchange between patient and clinician must be confined to that provided by a few pushbuttons for the patient and a few prerecorded messages for the computer. Because of this limited communication between patient and computer, the usual radial line or sunburst chart is modified to provide a three- or four-choice series of gratings, which allow the finding of the axis of astigmatism within 5°.

Cross-cylinder tests are also administered as pairs of lenses; the patient is asked to say which of a pair is better, lens number one or lens number two. In this way the cylindrical axis and power for correction of astigmatism can be ascertained, along with the values found from the radial line or grating charts.

In any case, a complete subjective examination can be administered by a computer system that can provide a prescription yielding maximum visual acuity.

6 *Final Decision and Prescription*

This is the *human* part of the system, by design. Even if it were possible to automate it with the current state of technology it would be wrong to attempt to do so. This part allows the patient to make any views, ideas, or feelings known verbally. It provides a means of human control and validation of both automated and manual procedures up to this point. The clinician reviews the patient's printout. After a discussion with him, the doctor makes the final decision including a possible prescription; that terminates the examination. If the patient needs spectacles or any other attention he is referred to the appropriate specialist and place.

The introduction and principles offered here are not a substitute for a more profound knowledge of the field of eye examination as it has developed in the past century or so. The reader should consult Southhall 1936, Lawrance and Wood 1936, Emsley 1952 and 1953, Duke-Elder and Abrams 1970, and Borish 1970 for general texts on eye examination and optics.

The Need for Automation in Eye Examinations

It is easy for one immersed in its development to assume that automation is the wave of the future and need not be justified. Nevertheless it is important to make a hard-headed evaluation or analysis to be sure that change is being suggested for the benefits it will bring rather than representing change for the sake of change.

Perhaps the best approach is to put automation aside for the moment and discuss how eye examinations should be improved without regard to the method. Later the methods of automation by which these goals might be effected can be considered.

It goes without saying that eye examinations, as well as other health-care activities, should be improved. They should be more accurate or valid. They should be less costly. They should detect insidious, irreversible diseases early, in order to arrest them before significant function is lost. They should be readily accessible.

Greater accuracy or validity in an eye examination is not a pressing need in view of the generally satisfactory procedures currently available. Basic research on the function of the visual system will no doubt lead to improvements in this direction. The exception to adequate examination procedures lies in what could be provided for the infant population. Knowledge as to the human critical or sensitive period and its significance, along with acuity measurements by visual evoked potential, should fill the theoretical and technological gap here. However, automation per se will be of little help except to reduce the time it takes the doctor to perform the examination. Initially it will be necessary to strive to keep the quality of the automated parts of the examination up to the best of current manual practice. Early attempts have shown some success, as may be seen towards the end of this chapter.

A reduction of cost has been the impetus for automation in all the fields it has come to dominate. A computer-controlled traffic light is less expensive than a policeman. A computerized billing system is far less costly than the bookkeepers who would do the same job manually.

Probably the most important contribution automation can make to eye examinations is an economic one. Later, evidence will be presented to show how an automated system could reduce the cost of eye examination markedly. It has been the general experience in the development of automation that the ratio of manual to automated cost continues to rise. The principal barriers in automating are the design and development costs, which may be of a nature and magnitude that do not make it clearly profitable for early private commercial development.

Automation can help in providing better eye and vision care. Automation comes after procedures are known, reasonably understood, codified, and reduced to flow charts and algorithms. It must be based on rules that can be specified in a flow chart. But automation is not expected to make new discoveries, although computer methods can readily keep and calculate statistics that may point to improved testing. Research and development are not the major thrust here. Computers bring the gift of perfect memory, incredible speed, indefatigability, but not yet cerebration in its best human sense. At present machines must be limited to do what can be reduced to a relatively simple set of rules.

Access to eye examinations and other health-care facilities is not only a matter of physical access, although that too may play a part. Sometimes economic barriers prevent people from obtaining proper care, especially when there is no obvious need or symptom. It takes foresight to seek an examination for the possible prevention of symptomless diseases that lead to irreversible deleterious effects. There are also cultural barriers, including language. Access can be increased by reduced cost and also by the use of appropriate languages in the various audio memories which provide the questions, instructions, and commands. The printouts for the doctor remain, of course, in his language regardless of the one used for the patient.

Access is also increased by having an eye examination facility as part of a large health center or hospital outpatient service, fed by satellite health clinics in the various neighborhoods.

Under present conditions the current supply of eye examinations is generally assumed to be in equilibrium with the demand. Of course, conditions can change rapidly. A new diagnostic method or cure for an insidious disease could shift the balance. Or, if the cultural and economic barriers were to be overcome, the demand might well outpace the supply. Further specialization (for example through new developments in contact-lens materials), which increases that demand, would reduce the number of clinicians for general eye examinations and therefore the supply. New developments in the detection of disease, geriatric visual care, and pediatric visual developmental problems not accessible to automation would also reduce the general supply. The increase of professional manpower has been a governmental goal. Federal agencies have provided subsidies to schools of optometry for some years without striking results. For example, about the same number of optometrists are practicing today as 20 years ago, although many of them now are much better trained. During the same period the number of board-certified ophthalmologists has perhaps doubled. It is not clear how many of them can be considered as numerical replacements for the reduction in the number of eye physicians who had not comparable specialized training (Hayes and Randall 1974). The general trend to better training ideally complements automation, which can compensate in part for the reduced numbers but could not compensate for any reduced quality of the clinicians.

A general eye examination includes (1) the determination of visual acuities (with the naked eye, and with old spectacles and new), (2) screening for disease (including the use of an ophthalmoscope, tonometer, and tangent screen, and, if indicated, corneal microscope-slit lamp), and (3) a determination of the refractive status of the eye (a subjective eye examination and if necessary an objective one also). It excludes extensive medical diagnosis, medical treatment, and surgery.

There are no direct statistics on the supply or demand of general eye examinations in the USA. However, figures can be obtained if we make a few reasonable assumptions. It is known that there about 21 000 optometrists and 9000 ophthalmologists. They include those who do not spend most of their time performing examinations. Some are in schools, colleges, and universities; some are in government service, including public health and the armed forces; and others have gone to business and industry. Among the ophthalmologists, many devote a good part of

their time to specialized eye examinations for medical therapy and surgery.

It can be assumed that 95% of the optometrists' time is concerned with general eye examinations and 60 to 75% of the ophthalmologists'.

	Number of practitioners (thousands)	Direct patient care (90%) (thousands)	% Time eye-care examination (thousands)	Full-time equivalents (thousands)
OD	21	18.9	95	17.95
MD	9	8.1	60-75	{4.86 / 6.08
Total	30	27.0		22.81-24.03

The number of eye examinations performed per working day varies from about 5 to 20 patients. It is noteworthy that optometrists who like to spend as much as an hour or more with each patient do so with the conviction that this thoroughness results in better care. They feel that examining more than eight or so patients a day is not in the best interest of their patients. The ophthalmologist who believes that the essentials of an examination can be accomplished in 15 or 20 minutes sees no ethical or technical problem in handling 20 patients a day or more. (A well-known Dutch ophthalmology professor once confessed that under their health insurance scheme he regularly saw 80 patients a day, which he did not consider unreasonable!)

It is assumed that a working year has 200 working days. The average optometrist provides 8.9 examinations per day; the average ophthalmologist, 17.8 (Hayes and Randall 1974).

Examinations/year-doctor							FTE (thousands)	Exams/year (millions)
OD	200 days/year	×	8.9 exams/day	=	1780 exams/year	×	17.95	31.95
MD	200 days/year	×	17.8 exams/day	=	3560 exams/year	×	{4.86 / 6.08	17.30 / 21.64
								49.25-53.59

We can take as a round number a supply of 50 million general eye examinations per year in the USA.

The U.S. population is more than 210 million, which gives an average of one examination from 4.26 to 3.91 or about every 4 years. The figure seems reasonable. Some never have an examination until forced to have one by presbyopia. The first encounter may occur in an ill-illuminated booth with a telephone directory in the 4th to 5th decade of life. Others, because of refractive problems, have had frequent examinations since starting school.

If it were assumed that everyone should have an annual eye examination (equal to the frequency recommended for general physical examinations and half that recommended for dental examinations) the annual number of examinations demanded would be more than four times the current calculated value. It is likely that the present capacity for examinations could be enlarged to some extent. Ophthalmologists appear to be working on general eye examinations at capacity (judging from the weeks to months delay in obtaining an appointment for this service), but optometrists by and large do not. If they could increase their capacity by about 20% it would mean an increase of 21 000 × 0.2, which comes to the equivalent of 4200 more doctors or 8.4 million more examinations per year. This is a sizable increase over the 50-million supply, but not much more than a drop in the bucket towards a potential 210-million demand. Furthermore, increases in demand that take up the last reserve slack in capacity are likely in any free market economy to push up prices.

It appears that there is an important need for automation in general eye examinations if we are not to have the demand outstrip the supply. To build, test, and prove a large-scale system such as that proposed in the following section of this chapter (Modular Computer-assisted Eye Examination Facilities) would take 4-6 years. To build and distribute such systems on a national scale might require another 6-10 years. In order to prepare for conditions in 10-16 years, it is necessary to start planning and building now.

In summary, there may well be a current potential demand for eye examinations that goes unfulfilled because of difficulties of access, cost, and cultural and linguistic barriers. In the foreseeable future the highly trained personnel required for eye examinations will be less available for general eye examinations, because of the need for their specialized skill in directions that are likely to expand and cannot be automated. These directions include contact lenses, early detection and treatment of diseases, and the eye examination and treatment of infants within their sensitive period. In preparation for the future supply of adequate numbers of eye examinations, a minimum of a 10-year lag must be reckoned between the decision to increase capacity and the time of achieving it on a national scale.

Modular Computer-assisted Eye Examination Facilities

The computer-assisted eye examination facility design must center around the doctor. He is in complete control. The floor organization and equipment are there only to allow him to take care of his patients more effectively and efficiently. It is therefore necessary to design the system around him.

One of the complications in drawing a design is that there are two kinds of doctors, the optometrist and the ophthalmologist. Each tends to have a somewhat disparate outlook on the performance of essentially the same clinical task, so that it has been found necessary to have at least two different designs. As long as these differences are kept clearly in mind, it is not a difficult task to design two systems that will make the different operational conditions into a more effective service.

The doctor-oriented system must be designed to provide the doctor with the specific flow rate of patients that meets his capacity to provide the final judgment and prescription. Optometrists in general take more measurements on a patient than do ophthalmologists. It is beyond the scope of our treatment to discuss what measurements are most valuable and whether these additional data are necessary or even desirable. A complete manual optometric examination requires a period of approximately one hour per patient. Some optometrists may spend only 15 minutes with a patient, but by and large they consider this a minimum time, to be done only under conditions that are somewhat stressful, such as in working directly for a large health plan or government agency. Calculating the actual examination time is not simple because the hour mentioned may well include a frame fitting, choice of frame styling, and the making of financial arrangements. The ophthalmologist, on the other hand, may often feel that a 15-minute examination is easily adequate. In fact, a survey of some ophthalmologists who use automated retinoscopes revealed (Decker 1975) that they reported seeing from 75 to 350 patients per week! For a 5-day week, that comes to a maximum of 70 patients per day. There is no easy way to determine how much time is necessary for each patient. Perhaps the most rational way is to determine the time required to provide satisfaction of the patient with his visit and his spectacles, if any. It is also desirable to have some measure of visual efficacy with the prescription. These criteria are very difficult since it is not clear how patient satisfaction or visual efficacy should be measured. In any case, currently one can only guess (Scylla) if an examination period is too long from an economic point of view, or (Charybdis) too short from a patient satisfaction point of view. The degree of this trade-off, of course, may also depend on the individual patient.

We can now examine two floor plans, both centered on the doctor, one intended for the optometrist and the other, for the ophthalmologist. To provide a constant flow it is assumed that with computer assistance an optometrist would be able and willing to review at least four patients an hour, and an ophthalmologist, ten patients an hour.

The optometric plan shown in Fig. 1-1 includes as its basic feature four refraction rooms. At a maximum of a half-hour per refraction, these four rooms can feed to the doctor four patients an hour, one every 15 minutes. The rest of the facility is built upon this assumed flow. The patient comes into the waiting area where he is entered into the computer file by the receptionist at the reception desk. He is then taken to a room where a case-history interview is administered. There are three such rooms, based on the assumption that a case history will take no more than 30 minutes. It costs little to keep one room in reserve since additional case-history rooms require very little equipment as long as the computer aspect of it is already available on a timesharing or standby basis. After the case history, the patient is taken to the room where his visual acuity is measured. Next, the patient is ushered into the pathology room, where a technician performs visual fields and perhaps slit-lamp microscopy and ophthalmoscopy examinations. Fifteen minutes should be adequate time for these tests. Next, the patient is given an objective refraction, either with an automated retinoscope or by visual evoked potentials; and after that an automated subjective refraction is administered. Upon completion the patient is ushered into the doctor's room, where the doctor reviews the records which are rapidly generated on a fast line printer. The doctor may do some final checking and he may also perform an ophthalmoscopic examination. The patient is then released to go to the optician and/or business office.

An analysis of the computer equipment to be used for such a facility was made by Lee, Braswell, and Marg (submitted as a report to the U.S. Army Medical Research and Development Command, 1978). This plan is based on a centralized computer facility with a separate computer room. The advantage of having separate stations for the case history, pathology examination, acuity, objective refraction, and subjective refraction is that different specialized equipment can be kept in different rooms. In this way more expensive equipment is not lying idle while less expensive equipment is being used in the same room. A contrasting concept is the decentralized computer facility in which all testing for any patient is complete in any room, each of which has its own microcomputer facility completely independent of all others.

The ophthalmological model floor plan has six identical eye-examination rooms (Fig. 1-2). All the functions with any one patient, including the consultation with the doctor, are performed in the same room. The patient is seated by the technician and the initial information is entered at the teletypewriter terminal into the flexible-disk file. The clinician then takes the case history and visual fields. He may also perform an objective refraction. As the patient has completed the automated subjective eye examination a signal light appears over the outside door of the room to alert the doctor that the patient is ready for the final consultation. The doctor reviews the patient's printout and approves the prescription. The patient, with his disk file, then goes to ophthalmic dispensing and/or the business office where his disk file is taken and entered into a central combined disk file. His disk is then erased and released for another patient. There are three additional rooms solely for automatically determining the case history. They may be used in addition to case histories being administered automatically or manually in the eye-examination rooms for patients who are slow to respond.

Each room has its own microcomputer, which includes cathode-ray display, hard-copy printout, and a dual flexible disk. The program for the eye examination is on one disk and the patient's data file record is on the other. It is possible to put them both on one disk and use the other as a spare. All the computers are identical and interchangeable. If any computer is out of order, it is a simple job to substitute another one for it. Spare computers can be taken from different stations such as that of the program analyst or the case history, or even interchanged from the optician's room if necessary.

The six eye-examination rooms are calculated to provide a flow of about one patient every 5 minutes, or approximately ten patients per hour. This number is based on the assumption that each room will be used for an average of 30 minutes per patient.

By these semi-automated methods, and with the use of technical assistance, it can be seen that in principle the patient flow rate can be at least doubled from current practice. If the optometrist formerly took an hour and now takes 15 minutes, his productivity rate is

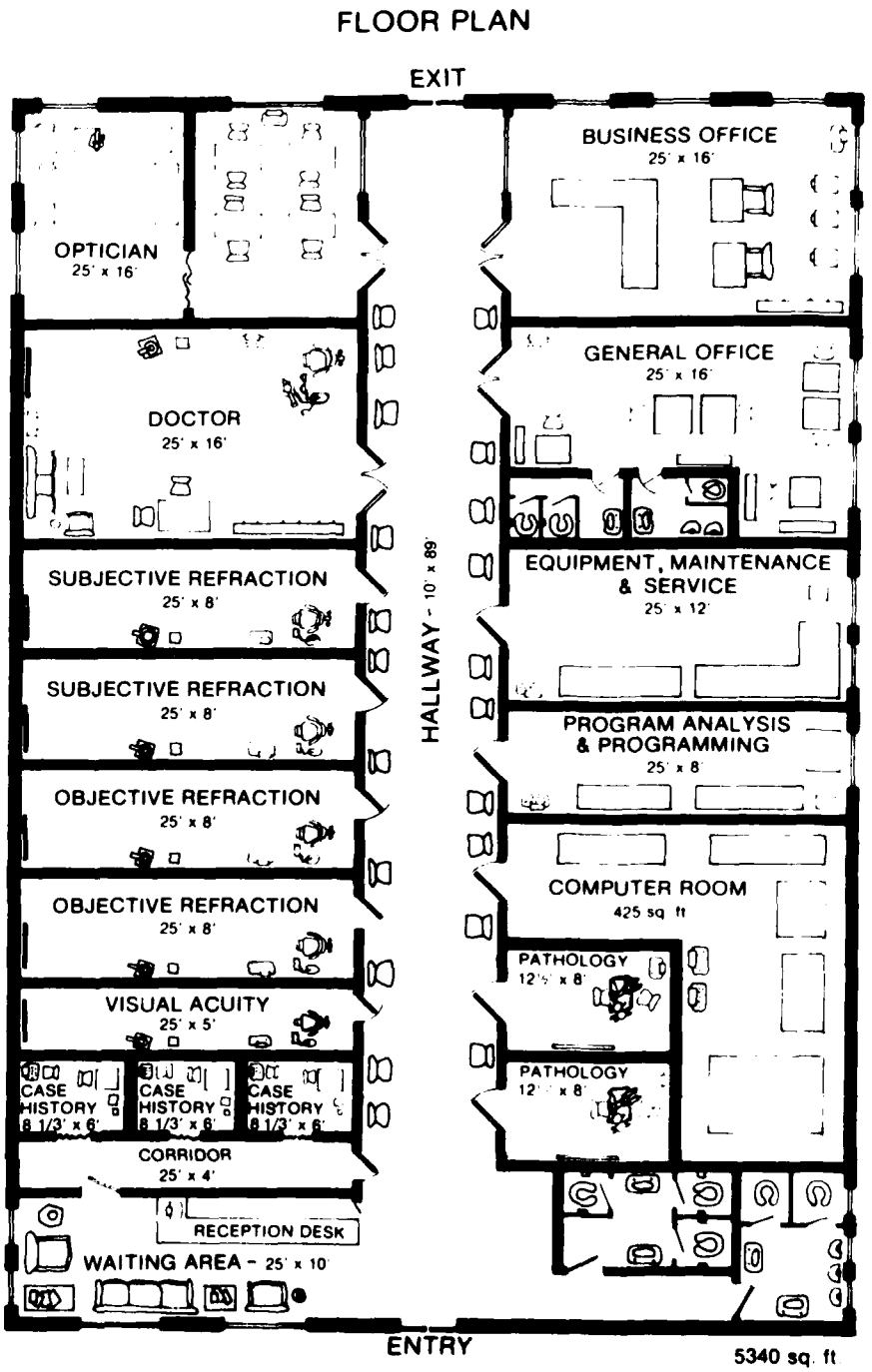

FIG. 1-1.—Optometric model floor plan.

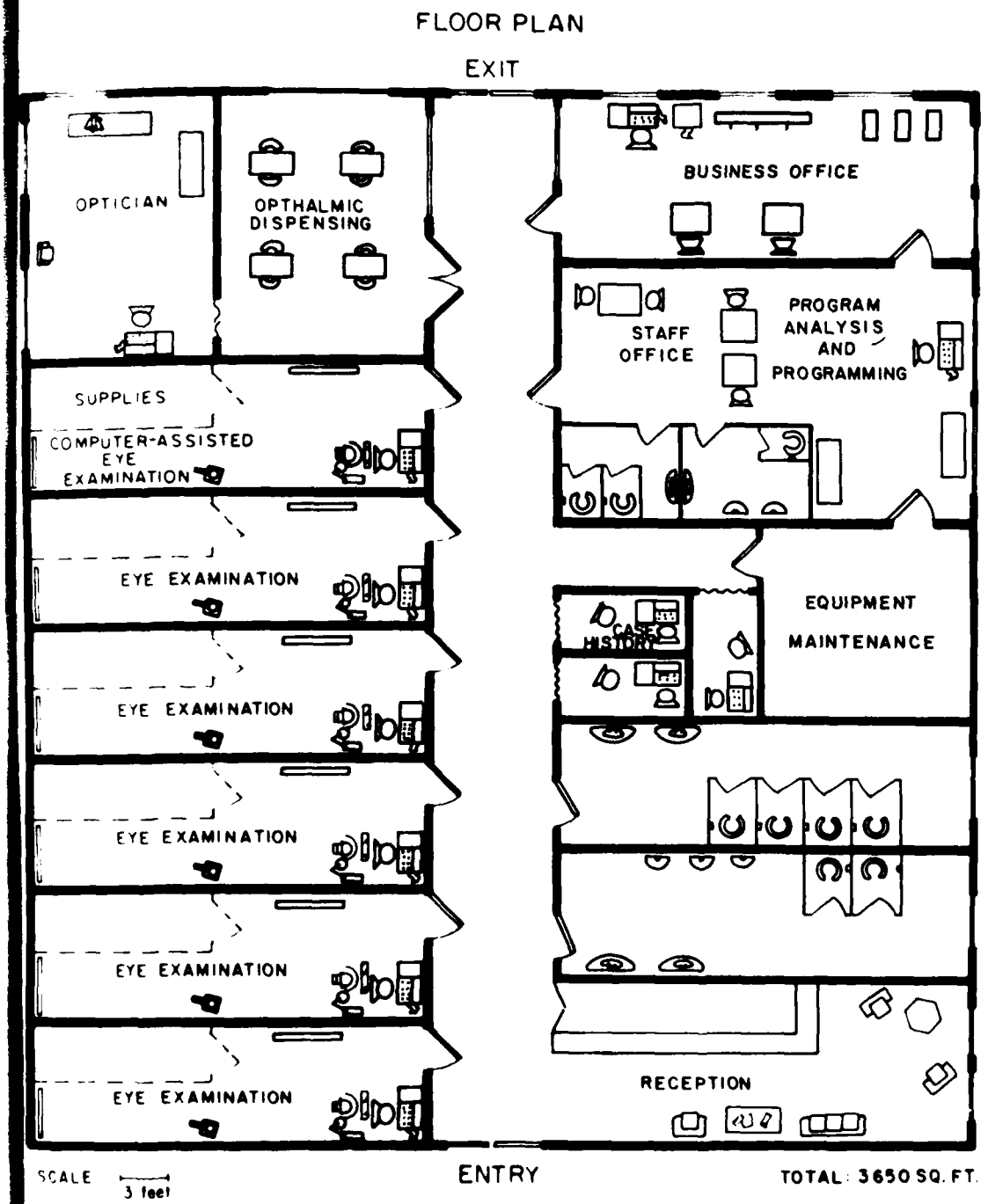

FIG. 1-2—Ophthalmological model floor plan.

quadrupled. If the ophthalmologist formerly took 15 minutes and now takes 5, his rate is tripled. These are, of course, only estimates. The final data will depend on actual clinical trials.

The second model, Fig. 1-2, is probably more efficient than the first. It is clearly more immune to an incapacitating breakdown. It could also be used for optometrists provided the necessary modifications were made to provide the desired rate of patient flow.

Economics

It has seemed self-evident, and even more so since the advent of microcomputers, that anything a computer can do will ultimately cost less than having a human being do it. Over the centuries, man's economic standard of living has continued to rise and especially so since the industrial revolution. Machines to a large extent have made the difference. Computers are carrying this development even further.

The cost of computation is decreasing at a rapid rate. It has been said that the costs are halved every computer generation of about 3 years. This trend is continuing but it obviously cannot continue indefinitely. Even if the reduction of computation costs reaches an asymptote, the increase in human costs (real income, corrected for inflation) in recent times has doubled about every 20 years (Gerard 1969). Obviously, if they have not done so already, these two curves will cross some time in the future, with the computer showing the economic advantage. However, one mitigating factor must be taken into account: the high cost of specialized input-output equipment. Unless it can be massproduced, which is not likely for the limited market, or at least computer produced (Cook 1975), its cost will increase in the future. The large development costs are an important factor, particularly that of manual programming in a low-level language, which is necessary with today's relatively inexpensive computers. This choice also weds one to a particular type of computer. It does not allow free changes of hardware to take advantage of the new and increased economies and flexibilities possible with newly developed models.

It can be deduced that if it were not for the large development costs to build, program, and debug a system, computer-assisted eye examination facilities would be proliferating today for economic reasons. Corporations take their responsibility to their stockholders seriously and they cannot reasonably take long chances on a system that is not clearly going to give a good return for the amount of investment capital risked. Initial financial support must come from government, philanthropic agencies, or from the eye professions themselves.

Aside from capital investment for development, the crucial economic question in computer-assisted eye examination is, how much of the doctor's time (which translates into money) does the computer system save? It is of course assumed that the quality of the examination is maintained. As was mentioned in a previous section of this chapter, optometrists generally like to spend 1 hour with a patient whereas ophthalmologists often feel 15 minutes is more than adequate. These figures were supported in a study by Hayes and Randall (1974) which showed that optometrists average 8.9 patients a day whereas ophthalmologists see 17.9.

Since part of the eye examination is automatable and other parts not, a study to determine how much time the optometrist spends performing automatable tasks was required. That was done with a stop watch (Marg and Ng 1972). Optometrists in their office practice were timed for each part of their examination activity. The results are shown in Table 1-1.

According to this division of activity, the optometrist appears to require only 10 minutes to do the external eye examination, ophthalmoscopy, and retinoscopy (which could be automated but may be done equally quickly manually by an experienced doctor) including 5 minutes for the final check, prescription, and discussion. On this basis an optometrist could see up to 6 patients an hour instead of about one.

Such figures can be deceptive and need validation. However, if they are only half correct, the savings would still be substantial. For example, if we take a remuneration of approximately $40 000 a year for an experienced optometrist or ophthalmologist, increasing his output six times could bring a value of $240 000 a year. The additional $200 000 can more than support a computer system facility once the development costs are paid. The savings could go toward

TABLE 1-1. Delegation of activities to computer and human assistants.

Time block (min)	Test	Optometrist time (min)	Human assistant time (min)	Computer assistant time freed (min)
41.4	external eye	0.6		
	case history			3.0*
	set up equipment		1.9	
	ophthalmoscopy	2.0		
	retinoscopy	1.9		
	subjective			6.4
41.4	muscle balance			1.5
	near tests			2.3
	bifocal adds			2.4
	keratometry		2.5	
	tonometry		3.0	
	styling frame selection			6.9*
	check old glasses		1.5	
	advice			5.5*
	adjustments		4.2	
	deliveries		7.0	
30.8†	write orders			5.8*
	check orders		13.8	
5.0	final check and discussion	5.0		
72.2		9.5	33.9	33.8

*Without a computer system, these tasks could be performed by human assistants. This adds up to 55.1 minutes for the human assistant's time and 22.1 minutes for that of the optometrist.

†These services are not necessary for each patient (for example those who may not need spectacles). This factor would reduce the total time from 72.2 to 46.4 minutes.

lower fees and higher salaries. Table 1-2 shows an estimated cost to build such a facility.

For comparison, three types of eye examination facilities were considered (Table 1-3): a single ophthalmologist with a manual system, one optometrist with a three-station automated system, and five optometrists working under manual conditions.

It is important to realize that these are cost figures. Because the ophthalmologist works faster his cost is lower in comparison with the optometrist in manual systems, $15 vs $19. (Optometrists would argue that faster examinations are less thorough and do not provide the best quality vision care.) However, the ophthalmologist usually charges the patient more. It is important to distinguish between the cost and the charge. The cost may be halved but the charge depends on socio-economic factors that may not be based in terms of health care.

It is possible that the cost per patient could be reduced significantly with such a system provided there is a reliably high rate of flow. Although the average cost to a patient in San Francisco for such an eye examination today (1977) is $30 for an optometrist and $40 for an ophthalmologist, the actual cost in a facility under public support appears to be closer to $10 per patient. Thus the saving would be of the order of half of this amount, or about $5 per patient based on clinic costs but $25 to $35 based on current office charges.

It should be noted that this transfer of activities partly to the computer and partly to the technician is well justified in modern technical practice. In fact, in all efficient fields of collective human endeavor, it is general practice to delegate as much as possible work to the less skilled, less talented, and less educated, provided there is no unacceptable loss of the quality of the performance. This trend reserves for the more skilled, talented, responsible, or more educated the more difficult tasks. In the ideal, a system is developed which permits each individual to rise to his highest level of competence and motivation with commensurate rewards.

The distribution of tasks among people and machines brings to mind the picture of the *Brave New World* in which Aldous Huxley divided the work according to the kinds of people that

TABLE 1-2. Equipment and capital cost for six stations as illustrated in Fig. 1-2.

Computer systems and interfaces	$140 000
Line printers	6 170
Projectors, random access	12 000
Refractors, computer actuated	100 000
Recorders, magnetic, audio	20 000
Tonometers, AO noncontact	24 000
Ophthalmic instruments, including slit lamps	29 000
Chairs and furniture	10 000
	$341 170

Amortized over 10 years excluding interest, $34 117 per year.

TABLE 1-3. Example of cost analysis for three types of eye-examination facilities.*

Description of system	Annual expense per unit	System** A	System** B	System** C
Equipment				
General Ophthalmic†	$ 500	$ 500	$ 500	$ 2 500
Furniture and space	500	500	1 000	1 500
Refractor (manual)†	500	500	1 000	1 500
Refractor (automated)†	5 700	0	17 100	0
†amortized over 10 years				
Personnel				
Ophthalmologist	40 000	40 000	0	0
Optometrist	30 000	0	30 000	150 000
Maintenance for automated system	666	0	2 000	0
Receptionist	10 000	10 000	10 000	10 000
Aide	8 000	8 000	16 000	24 000
Technician	12 000	0	12 000	0
	Annual total	$59 500	$89 600	$189 500
Assume 200 operating days per year:	Daily total	$300	$450	$950

*Devised by Dr. James Millott.

**System: A. 1 ophthalmologist with manual system: (20 patients/day)→$15/patient
B. 1 optometrist with 3 automated instruments: (48 patients/day)→$9/patient
C. 5 optometrists with manual system: (50 patients/day)→$19/patient

inhabited that world. At the top were the Alphas who were the intellectuals; then the subintellectual Betas, and down through the Gammas, Deltas, and finally the Epsilons. The last were small, simian-like semimorons who did all the most menial work. This imaginative picture does not seem to have taken into account the machine or the computer, nor has it taken into account the political philosophy (one man, one vote) that has been more strongly developing over the decades since the book was published. We all are, or believe we are, Alphas. The work of the Betas is being delegated to the computer and so on down the grading to the Epsilons, whose work has been given to machines. The Alphas of today are those who in the broadest sense control the computers and the machines. Even if Huxley's scheme were not an economic catastrophe it would require, as he himself made clear, authoritarian control, as well as a degree of docility that is not characteristic of our society.

As stated earlier, the future of computer-assisted eye examination rests squarely on its economics. However, history teaches us that it is difficult to predict the path of the adoption and use of new technology. For example, right after World War II the experts expected a private flying boom. Predictions were made that Model T airplanes would fill the air and we were told that we should not build bridges and freeways but small airports. These predictions did not

foresee the expansion of commercial air traffic, nor anticipate that jet planes could lead to mass transportation by air in place of large surface vessels (Drucker 1973). Another example is found in the computer which was born as a major scientific and technological revolution. Its main use initially was in science and warfare, not in business and government. Market research at that time concluded that 1000 computers would be needed by the year 2000. Now, only a quarter of a century later, there are more than 150 000 computers in the world (before the microprocessor revolution), most of them doing mundane bookkeeping work. The most successful prophet of technology, Jules Verne, predicted much of 20th century technical progress. Few scientists took him seriously at that time. But as prescient as he was, he anticipated no social change, but based his extraordinary visions upon an unchanged Victorian society and economy.

If specific technological prediction is difficult, it can be stated with confidence that technology generally continues to improve as does our ability to use it to solve our problems. What are the possibilities of improving the computer-assisted eye examination in the future? The future may be divided into the near and distant, the near future presenting possibilities that can be achieved now at a reasonable cost of reproduction with the necessary application of time and resources. The far future often becomes visionary without the kinds of limits which prevent excursions into science fiction. To avoid the classical errors of the visionary, it is necessary not to look beyond the horizon.

The computer is being made more reliable and flexible by the elimination of certain components that are mechanically controlled and activated. These changes include conversion of the cartridge tape recorders to speech converters. A new chip produced by Harris Semiconductor does this function with continuously variable slope delta modulation. It requires 16 kilobits per second of speech memory and gives telephone quality speech without moving parts. As the cost of solid-state read-only memory is reduced, longer messages will be more economically feasible.

The random-access slide projector can also be replaced by television or other display techniques, without moving parts. Such schemes are currently being designed and constructed.

Newly developed flexible disks would provide faster access to data than the digital magnetic tapes currently in use. It is not only the cost of the new equipment, but also the reprogramming costs that must be overcome for a changeover.

Microprocessors are obviously the wave of the future, although our extensive investment in programming the present project confines us to the PDP-8/E hardware configuration. An integrated-circuit chip compatible with these programs, the Intersil IM 6100, is being adopted. Other microprocessors are being used to replace the hardwire organization of the computer refractor interface. Although there are no moving parts to replace here, microprocessors provide a reduction in the number of chips needed and lower power requirements, and give greater flexibility in the organization of the system.

Aside from maximizing reliability, probably the greatest amount of effort should be made in the optometric flow charts. These routines were devised by clinicians from a clinical point of view. It might be desirable to put some of the assumptions made in the initial design of the parts of these tests to a more scientific rather than overall clinical validation. This might be a long and difficult project, but important in considering the future without limitations of time.

Computer-assisted eye examination is here. There is much to be done to improve it and to propagate it. Refractor III system is a smart instrument that can provide a useful prescription for most clinical patients. Our calculations indicate that it will be an economically viable instrument in a clinical setting with the proper flow of patients. Although it is smart for an instrument, it is certainly not as clever as a good clinician. When it is under the control of and used as an aid by well-qualified clinicians, the final quality of the system's work is high.

Some colleagues appear concerned that computers may displace them. The history of computer applications does not give much support to this fear. A system should reduce costs and increase the access of eye examinations. If employed rapidly on a large scale, computer assistance might cause some dislocations in the eye-examining professions. In the longer run there is a large underserved population to which the released talent could be applied. The most neglected population is comprised of young infants. Infants generally are not routinely examined and the newly

available techniques of determining their eye conditions in order to prevent amblyopia and perhaps squint are not being exploited (Marg et al. 1976). These kinds of examinations are not completely automatable. The released professional manpower that would come of general automation could serve here.

In their brief history of some twenty-five years, computers have in general not replaced, but have tended to displace people to other kinds of nonautomatable jobs. Certainly a strong need will remain for the optometrist and the physician in the foreseeable future. But the more we can help by relieving them of some of the more routine and rote load, the more economical will be the system and the better both optometrists and physicians will be utilized for the health of us all.

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Chapter 2
AN HISTORICAL REVIEW OF OPTOMETRIC PRINCIPLES AND TECHNIQUES

Arthur G. Bennett

AFTER THE RESEARCHES of Rosen and earlier writers into all the available evidence, there seems little doubt that spectacles first appeared around the year 1280, in Italy. At that time little was known about the properties of lenses and even less about the workings of the eye. For the following 600 years or so, self-selection from a range of ready-made spectacles remained the only generally available method of procurement.

The aim of this chapter is to give a broad picture of the development of refractive techniques. For this purpose, the term 'refraction' is taken to mean the assessment of visual acuity and ametropia by science-based methods. The main paths of progress in this field are flanked with numerous byways which offer fascinating exploration to those with an historical bent. Because of space limitations, emphasis has been placed on the earlier and the lesser-known contributions to this subject, particularly when they are of special inherent interest. In general, the survey has also been limited to the aspects and methods of refraction which, without too much effort of imagination, can be considered relevant to the evolution of computerized optometry.

Basic Geometrical Optics

It was not until the 17th century that the foundations of geometrical optics were laid. The first great contribution during this epoch was made by Johannes Kepler (1571-1630). In his short but remarkable treatise *Dioptrice*, published in 1611, the main properties of lenses and optical systems are expounded on the basis of what we would now term the paraxial law of refraction. Kepler well understood the limitations of this approximation and sought in vain to deduce the true relationship between the angles of incidence and deviation. Though this result eluded him, he nevertheless arrived at an expression giving only very small errors, even at large angles of incidence.

It is to Willebrord Snell (1580-1626) that the discovery of the true law of refraction is generally credited. The first treatise on optics to be published after this event and to profit by it was *La Dioptrique* (1637) by René Descartes (1596-1650), the French mathematician and philosopher. Descartes was particularly interested in aspherical surfaces as a means of correcting spherical aberration. Unfortunately, this is a field in which mathematics rapidly outpaces technology.

Although it was easily within his powers, had he chosen to tackle the problem, Kepler did not obtain a general expression for the paraxial focal length of a thin lens in terms of its radii of curvature. Credit for this important step forward must be given to the Italian mathematician Bonaventura Cavalieri (1598-1647). In his *Exercitationes geometricae sex*,* published in 1647

*Despite appearances, an accurate English version of this title would be 'Six Dissertations on Geometry'.

shortly before his death, Cavalieri established a general formula but its validity rests on the assumption that the refractive index of the lens material is 1.5. In fact, what he did was to generalize Kepler's treatment of refraction by a lens on the basis of the approximate law of refraction. News of the discovery of the true law does not appear to have reached him. In the absence of a sign convention—a concept as yet unknown in geometrical optics—Cavalieri was obliged to restate his general expression in the form of rules for various spherical lens forms.

The task of applying the true law of refraction to the construction of a mathematical theory of geometrical optics was undertaken independently by two contemporaries of an entirely different stamp, Isaac Barrow (1630-1677) and Christiaan Huygens (1629-1695). Barrow, one of Newton's mentors at Trinity College in Cambridge, was above all a geometer of genius but was also a classical scholar and student of divinity, for which he abandoned his chair as the first Lucasian Professor of Mathematics in favor of his former pupil, Newton. Although Barrow's *Lectiones XVIII opticorum phaenomenon*, published in 1669, is a work of the greatest historical importance and interest, the lack of an English translation has doomed it to undeserved neglect.*

Unlike Barrow, whose interest in optics was purely intellectual, Huygens was endowed with surpassing practical and experimental skill in addition to his other exceptional powers. He seems to have begun his studies in geometrical optics somewhat earlier in life than Barrow, whose first university chair was in Greek.

It was Huygens's original intention to publish the results of these earlier researches in 1653, by which time he had already covered an important part of the field. However, this and later plans for publication were shelved for various reasons. Instead, the scope of the work was expanded to form a treatise in three parts, generally known by its French title, *La Dioptrique*; unfortunately it did not appear in print until 1703, several years after Huygens's death.

Questions of priority as between Huygens and Barrow are quite inappropriate. Barrow's *Lectiones XVIII* first gave to the world expressions for conjugate foci relationships for plane and curved surfaces, both at normal and oblique incidence (in the tangential plane). It also contained some beautiful graphical constructions, two of which lead directly to the aplanatic points of a spherical refracting surface. Barrow also anticipated Airy and Petzval in his investigations of image curvature. Some of his results had already been obtained, though not published, by Huygens, who used a different approach. A comparison of their methods makes a fascinating study for the specialist in geometrical optics.

In the fourteenth of his *Lectiones XVIII*, Barrow gave the following construction for a spectacle lens to aid a myope. It is worthy of reproduction here because it is the first published procedure for making a spectacle lens on a demonstrably sound optical basis.

Figure 2-1 is essentially the same as Barrow's Fig. 163, with the same lettering, but reversed right to left. The lens is to be designed for a myope who cannot see clearly beyond the point Z but who wishes to see clearly the point A at a specified distance. The refractive indices of the lens material and air are assumed to be in the ratio of 5 to 3 (i.e., $n = 1.667$). First, the positions of the vertices B and D are located on the optical axis so as to give a suitable lens thickness and lens-eye separation. Next, the axial point C is located from the formula

$$CB = 2AB \times ZB/(5AB - 3ZB)$$

The point C is the center of curvature of the first (concave) surface of the required lens, and Z is the center of curvature of the second (convex) surface. The work of forming an image of A at Z is thus performed by the first surface only. For the second refraction, the image remains in the same plane, at the center of curvature of the surface.

The result of this construction is a meniscus lens which we should now regard as the wrong way around. Nevertheless, as Barrow pointed out, under certain conditions it is aplanatic, that is to say, free from spherical aberration with respect to the conjugate points A and Z. *All* the rays diverging from A would then, after refraction, appear to emanate from Z.

*Happily, there is some prospect that a reliable English translation, already in existence, may be soon published in England.

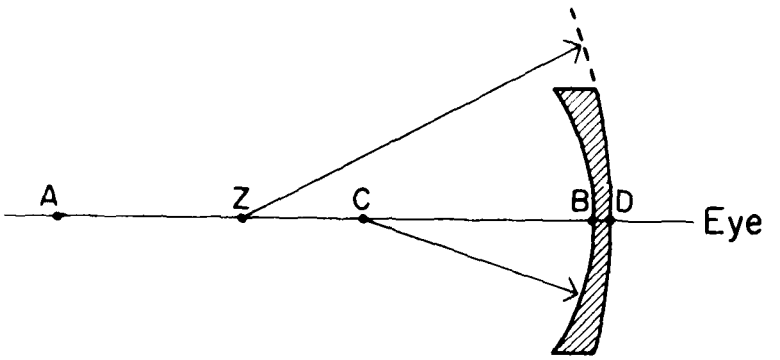

FIG. 2.1. Isaac Barrow's construction (1669) for a lens to enable a myope with his far point at Z to see clearly at I.

If we simply denote the refractive index of the lens material by n, the object distance AB by l and the image distance ZB by l', Barrow's expression assumes the generalized form

$$CB = (n - 1)AB \times ZB/[(n \times AB) - ZB]$$

or

$$r = (n - 1)ll'/(nl - l')$$

This latter expression, in turn, is simply the familiar

$$\frac{n'}{l'} - \frac{n}{l} = \frac{n' - n}{r}$$

applied to refraction at an air to glass surface.

A similar construction was given for a lens to enable a presbyope to see clearly at a specified shorter distance than his near point.

Huygens, too, gave rules for dealing with these visual situations but his approach was quite different. It was based on determining the necessary radius of curvature for a flat lens of symmetrical form. He was well aware that the radius of curvature of such a lens is equal to its focal length if the refractive index of the material is 1.5. He also pointed out that a lens of any other form could be used, provided it had the same focal length.

The introduction of a sign convention was a notable step forward in geometrical optics. In the words of its originator: "The excellence of the modern geometry is in nothing more evident, than in those full and adequate solutions it gives to problems; representing all the possible cases of one view ... Of this I now design to give an instance in the doctrine of dioptrics." These lines were written by Edmund Halley (1656-1742), the English astronomer (after whom 'Halley's comet' is named) in the opening paragraph of a Royal Society paper published in 1690. In this paper, Halley deduced a general expression for refraction by a thick lens, the object distance being measured from the first surface and the image distance from the second. Halley's sign convention for object and image distances corresponds to the 'real is positive' system. Radii of curvature were taken as positive for convex surfaces and negative for concave surfaces.

The first major work on geometrical optics to employ a sign convention was written by J. F. W. Herschel (1792-1871), another eminent astronomer, in 1827. It is particularly noteworthy that the sign convention he devised is that which has ultimately gained almost universal acceptance in the world of optometry and optometric education. Further reference to Herschel's work will be made in a later section of this chapter.

Physiological Optics

By the end of the 17th century the foundations of geometrical optics had been firmly laid. So, in the main, had those of physiological optics, for which Kepler, Scheiner, and Huygens were largely responsible.

Kepler's *Dioptrice* contains a number of propositions relating to the eye and vision, but his main contribution in this field is embodied in an earlier treatise, the *Ad Vitellionem paralipomena* published in 1604. In this work, Kepler showed an astonishing grasp of ocular anatomy and of the basic visual processes. Unlike his most distinguished predecessors, he recognized the retina as a sensory network and as the intended location of the optical image, which he also knew to be inverted.

In 1619 Christoph Scheiner (1573-1650), an influential member of the Jesuit order, published *Oculus, hoc est: fundamentum opticum,* which is regarded as the first formal treatise on physiological optics. Among Scheiner's many gifts were acute powers of observation and great experimental skill. For example, to test the truth of Kepler's assertion that the retinal image is inverted, he cut away part of the tissue of various eyes so that the retinal image could be clearly seen from a back view. Unfortunately, Scheiner's treatise does not appear to have been translated in full into any living language. As a result he has suffered a fate similar to Barrow's—the scope and magnitude of his achievements are generally unappreciated. Nevertheless, his name has been perpetuated by one of his inventions, the well-known Scheiner disk, in which two narrowly separated pinholes or slits, placed in front of the pupil, cause a doubling of the retinal image when it is out of focus.

Huygens's greatest contribution to physiological optics was in ocular dioptrics. In the earlier part of his *Dioptrique*, written by the year 1653, he described what we should now term a 'reduced eye,' thus anticipating Listing by nearly 200 years. In fact, Huygens's was a more sophisticated optical design. He assigned to it a refractive index of 4/3, the overall length being four times the radius of curvature of the single refracting surface. The eye was hence emmetropic. Further, by making the refracting surface concentric with the retina and placing the pupil at this common center of curvature, Huygens so arranged matters that narrow parallel pencils entering the eye from any direction would be accurately focused on the curved retina.

Huygens also gave a cross-sectional diagram of a schematic eye, the only fault in which is that the cornea was given the profile of a strong converging meniscus lens. Several years later, in what became the second *Complément* to his *Dioptrique,* Huygens gave a more accurate diagram with a list of dimensions, based on the dissection of a human eye performed in his presence. In this addendum Huygens makes many acute comments on the structure of the eye, which he held to be the Supreme Author's most marvelous creation. He concludes with a brief discussion of binocular vision, the theory of corresponding points, and physiological diplopia.

There were many others, of course, who contributed to the growth of knowledge and understanding of visual science at this period, for example the French Jesuit Claude Dechales (1621-1678). In 1674 he published a work in four large volumes, his *Cursus seu mundus mathematicus,* which is an astonishing compendium of scientific knowledge, embracing mathematics, astronomy, physics, civil and military architecture, perspective, navigation, music, pyrotechnics, and other subjects. Donders expressed particular admiration for Dechales's discussion of myopia, based on his own observations and experiences as a myope. Even without a knowledge of Latin, a fair idea of Dechales's work can be gleaned from the numerous diagrams, one of which is reproduced here as Fig. 2–2. It illustrates the action of a small aperture in reducing the size of the retinal blur circles of an out-of-focus image.

Despite the great progress made during the 17th century, some important sectors remained in obscurity. Ametropia was conceived as being of only two varieties, myopia and presbyopia, caused by an excess or deficiency in the power of the crystalline lens. The role of the cornea as a strong converging element was not generally understood. As late as the turn of the century, by which time their authors should have known better, the diagrams in a number of practical treatises showed parallel pencils of rays passing undeviated through the cornea, as though it were a plane surface.

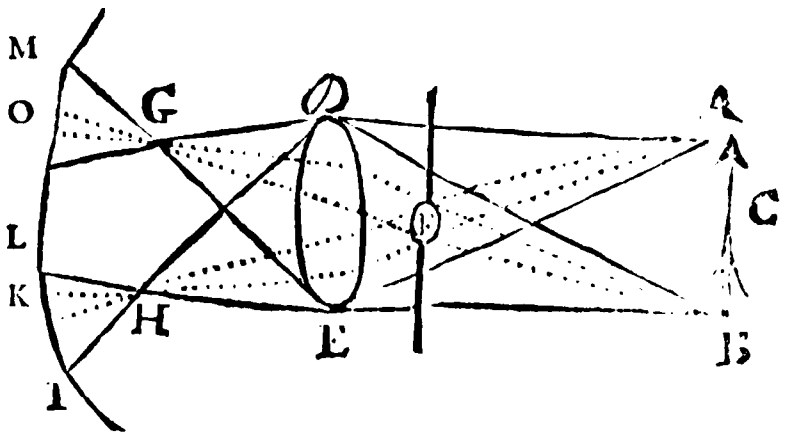

FIG. 2.2. Dechales's illustration (1674) of the reduction in the size of retinal blur circles when a pinhole *F* is placed in front of the pupil.

Although Descartes had correctly ascribed accommodation to a change in the curvature of the crystalline lens, illustrating this explanation with a beautiful diagram, this theory was not universally accepted. Huygens originally subscribed to it, though he believed that a forward shift of the lens was possibly an auxiliary mechanism. Indeed, later in life he inclined to the view that this latter explanation was sufficient on its own. On the data then available, no firm conclusion could be reached. The issue was finally settled in the 1790s by the classic experiments of Thomas Young.

The distinction between presbyopia (as we now use the term) and hypermetropia proved difficult to grasp and remained in obscurity for a very long period of time. It was Frans Cornelis Donders (1818-1889), aptly called "the father of modern refraction," who finally dispelled the confusion in his classic work *Accommodation and Refraction of the Eye*, first published in 1864 in an English translation.

Assessment of Visual Acuity

Visual acuity is a complex attribute in which the eye's resolving power plays a major but not an exclusive role. Depending on the nature of the test object, other perceptual factors may be brought into play. Scientific assessment of visual acuity therefore demands standardized test objects, procedures, and viewing conditions (illumination, contrast, etc.), as well as a rational notation for recording it.

The most notable of the earlier experimenters in this field was doubtless Johann Tobias Mayer (1723-1762), a professor of mathematics at Göttingen and a renowned astronomer. His lamentably early death is attributed to continual overwork. In addition to gratings of two different patterns, one of the test objects Mayer used was a grid of horizontal and vertical lines. Another was the now familiar checkerboard pattern, recently discovered to be a most suitable test object for procedures based on visually evoked potentials.

Mayer determined the *minimum separabile* for all four of these test objects, placing a candle at different distances so as to vary the illumination. By this means he was able to compile a table showing the *minimum separabile* (which he denoted by *S* in seconds of arc) for each test object at various levels of illumination. He then devised a general expression for each test object, relating the value of *S* to the distance of the candle from the chart. It was a remarkable pioneer effort.

For clinical use, the chief requirements of a subjective test of visual acuity are that it should be simple to operate and readily understood by the subject. On these grounds the appeal

of letters as test objects is easily understandable. They require no explanation and are convenient to the subject. The use of letters in a sequence of sizes seems to have originated with Heinrich Küchler (1811-1873). In 1843 he produced a set of three reading charts, all of the same basic design. Each one comprised 12 numbered lines of type in the traditional Gothic script then employed by German printers. Each line consisted of a single word in lower-case type except for the initial capital letter. The largest size was at the top; the individual words contained more and more letters as the size decreased, in a somewhat irregular progression. Küchler's chart met with little success, probably because the smallest line of type was still much too large to provide a critical test of visual acuity.

Eleven years later, Eduard von Jaeger (1818-1884), professor of ophthalmology at Vienna, produced a set of *Schrift-Scalen* on somewhat similar lines that rapidly achieved the success that had eluded Küchler. One reason was doubtless that Jaeger's chart included at least four sizes of type smaller than Küchler's, though an exact comparison is difficult because Jaeger employed a Roman style typeface. Another difference was that in Jaeger's chart the sizes increased from the top downwards, No. 1 thus being the smallest. By way of further improvement, Jaeger provided two lines of connected reading matter in all sizes up to No. 10. Within a few years, versions of Jaeger's chart had been published in many languages and alphabets, including Greek, Hebrew and Russian. It is still widely used today for assessing near visual acuity. One defect is that the progression of sizes is based on availability and not on an orderly system. For this reason, the notation J1, J2, J3, J4, etc., used for record purposes has no significance beyond a method of labeling.

The now familiar letter chart for testing distance visual acuity was introduced by Herman Snellen (1834-1908) in 1862. Snellen was a junior colleague of Donders, who was then professor of ophthalmology at Utrecht. It was Donders who propounded the idea that the line widths and spaces of the individual test letters should be related to a visual angle of one minute of arc. Donders also suggested the method of recording acuity which later became known as the Snellen fraction. In this notation, the visual acuity or *visus V* is expressed as

$$V = d/D$$

in which d is the testing distance and D the distance at which the height of the smallest discernible line of letters subtends 5 minutes of arc.

Snellen's own contribution was still a considerable one. His complete set of 'optotypes' included near vision as well as distance charts printed in black on white, white on black, and in several different colors. There was also a chart presenting various arrangements of parallel lines to facilitate the testing of astigmatic subjects. In 1866 a chart of geometrical figures for testing illiterates was added, and in 1873 Snellen produced the well-known 'Illiterate E' chart which is still widely used. The typeface used by Snellen as a model for his letters was characterized by heavy ornamental cross strokes, or 'serifs.' Although this style retained its popularity for a great many years, there now seems to be a general preference for nonserif letters.

Following the Meter Convention of 1875, which established the metric system in some forty countries, Snellen adapted his distance types to a testing distance of 6 meters. Hitherto he had taken 20 (Paris) feet as the standard distance. (One Paris foot is approximately equal to 1.066 Anglo-American feet.)

The original progression of letter sizes seems to have been chosen by Snellen empirically; his distance chart provided the following seven lines: 20/20, 20/30, 20/40, 20/50, 20/70, 20/100, and 20/200. Considered as a whole, this series of D-values approximates roughly to a geometrical progression in which the seventh term is ten times the first term; the constant ratio (of each term to the preceding one) is thus $\sqrt[6]{10}$ or approximately 1.47.

After the appearance of Snellen's optotypes, which received a general welcome, suggestions for modifications and improvements came in from all quarters. In particular, the French ophthalmologist Ferdinand Monoyer (1836-1912) produced a chart in 1875 which is still used as a model in some European countries. It incorporated four important modifications. First,

Monoyer used nonserif letters of 5 × 4 construction (5 units in height and 4 units in width). Second, he introduced what might be termed the decimal-*V* notation in which, for example, $V = 0.25$ would be used in place of 20/80 or 6/24. Third, he chose a progression of sizes ranging from $V = 0.1$ to $V = 1$ in intervals of 0.1. This was a radical departure from Snellen's quasi-geometrical progression of sizes. Finally, Monoyer designed his chart for a testing distance of 5 meters.

From a scientific point of view, letters have several disadvantages as test objects. In 1899 the Swiss ophthalmologist Edmond Landolt (1846-1926) introduced his 'broken ring' or 'C' test, which overcomes many of the objections levelled at letters. It comes as no surprise that it has been adopted for many particular uses and has gained some acceptance in everyday optometric practice.

By the turn of the century, so many different versions of the Snellen chart had been produced that it had lost all semblance of a standard test from which comparable results could be expected. As the English ophthalmologist Hay wryly remarked, the amount of compensation for loss of vision awarded to a claimant in a lawsuit for damages might well depend on which of the conflicting expert witnesses the judge esteemed to be the "best liar."

Landolt's broken rings (in eight different orientations), supplemented by the numerals 0, 1, 4 and 7, formed the basis of the first distance test chart to become an official standard. It was formally adopted as such by the Eleventh International Ophthalmological Congress held in 1909. It soon became a dead letter. Unfortunately, the design of test charts is one of those subjects on which there are almost as many opinions as there are practitioners. Over the years, the style and proportions of the typeface, the selection of letters, the progression of sizes, the testing distance, and the notation to be employed have all given rise to acute controversy. For a detailed account of these arguments the interested reader is referred to an earlier paper by Bennett (1965a). A fresh attempt is now being made through the International Federation of Ophthalmological Societies to formulate a new standard chart acceptable to the majority of its members.

In view of this past history, the publication in 1968 of the British Standard BS 4274 for distance test charts can be hailed as an achievement because the committee responsible for its formulation represented not only ophthalmologists but also optometrists and dispensing opticians, as well as manufacturers. A German Standard, DIN 58 220, has since been published, giving details of a distance test chart composed of Landolt rings in eight different orientations. Levels of illumination and a standard procedure to be followed when using the chart are also specified.

This discussion has so far been confined to subjective tests of visual acuity. Objective methods are of much more recent origin and are the subject of Chap. 7.

Beginnings of Subjective Refraction

The idea of a subjective test, as distinct from trying on various ready-made spectacles with lenses of equal power, is implicit in the 'polyspherical lenses' invented by a German monk, Johann Zahn (1641-1707). They are described in the third volume of his *Oculus artificialis teledioptricus sive telescopium*, published in Wurzburg during 1685 and 1686.

Zahn's work is of wide scope, dealing with optics and optical instruments from a practical as well as a theoretical standpoint. In addition to his other abilities, Zahn was evidently a skilled lens maker, he described a grinding machine of his own construction. An English translation by Bennett, together with a commentary, of the chapter devoted to spectacles appeared in 1968.

The modern reader cannot fail to be struck by Zahn's clinical sense. Though paying them reverence, he will have nothing to do with the meager range of standard foci compiled by Sirturus and other writers. As he remarked, it is best not to fit the eyes to the lenses but the lenses to the eyes. He had taken note of a statement by Dechales that anisometropia is possible and confirmed its truth by his own observations.

Though warning against the premature use of spectacles and of corrections stronger than needed, Zahn did not shrink from high powers when necessary. He mentions a case in which he

prescribed -26 diopters (in our notation). One of the methods outlined by Zahn for testing a myope was to find the far point distance and make a lens of the same focal length.

Zahn was fully aware of the importance of correct centration, as shown by the following brief passage:

> When two lenses are combined [in a pair of spectacles] care must be taken that they do not cause the object to appear doubled, as occurs if they are not in the correct relative position; the frame should therefore be so adjusted that the lenses remain in their correct relationship with each other and do not, through careless fitting, impose a disagreeable burden on the sight and thus do more harm than good.

Figure 2-3 is reproduced from a handmade copy of Zahn's own illustration of his polyspherical lens, which might be styled the world's earliest and most compact refracting unit. The plus version was plano-convex in form and the minus version plano-concave. Each was made from a single piece of glass; the various concentric zones had different curvatures. Essentially the same technique is employed to produce 'upcurve' one-piece bifocals. In a concave polyspherical, the central circular portion necessarily has the steepest curvature, whereas in the convex it has the shallowest. Each lens provided a range of six different powers that could be brought in succession in front of the pupil; the width of the zones was just sufficient for this purpose.

It is clear that Zahn would not have been content with just one plus and one minus polyspherical but he gives no details of the foci he employed. He left it to any interested reader to draw up his own specifications.

It seems strange that over 150 years were still to elapse before the trial case appeared in its modern form. After the rapid advances of the 17th century, the impetus waned. From the standpoint of optometry the 18th century was a quiet one and no significant advances were made until it was nearing its end.

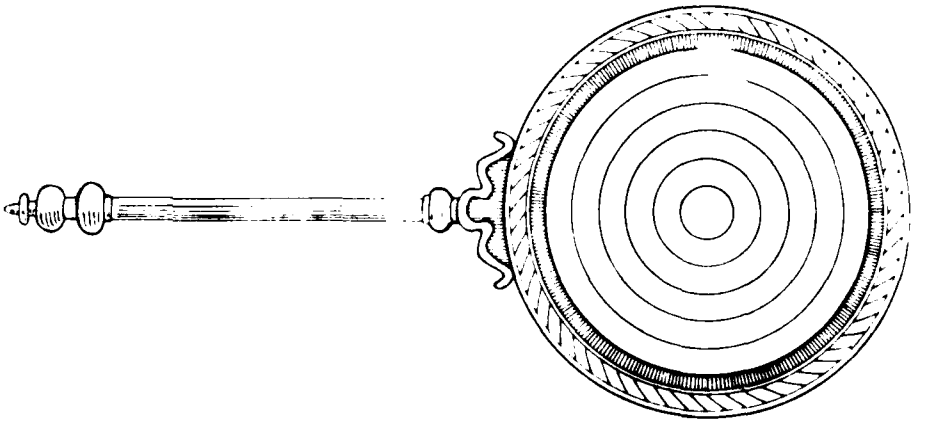

FIG. 2-3. Johann Zahn's 'polyspherical lens' used as a refracting unit (1685-86)

Astigmatism

As I have remarked elsewhere, astigmatism was a British invention and remained practically a British monopoly for nearly 150 years.

An astigmatic surface is one in which the curvature varies from a minimum in one principal meridian to a maximum in another perpendicular to it. It does not possess axial symmetry.

Astigmatic pencils may be divided into two main classes: those produced at normal incidence by an astigmatic (e.g., cylindrical or toroidal) refracting surface, and those produced at oblique incidence by a plane or spherical surface. The latter variety retains the essential features of the former, but in a more complex form arising from the lower degree of symmetry.

The geometry of an astigmatic pencil can be adequately visualized only as a three-dimensional construction. As long as consideration was restricted to rays in the plane of a diagram, the possibility of astigmatism could hardly have been imagined. It took the genius of Isaac Newton (1643-1727) to divine the existence of astigmatic imagery, though it was only astigmatism due to oblique incidence about which he wrote.

In his *Lectiones XVIII*, Barrow had given an elegant and correct expression for conjugate foci in the tangential (plane of diagram) section of a narrow obliquely refracted pencil. Newton supplied a graphical solution and added another for the sagittal section as well. He also touched on the problem of which cross section of an astigmatic pencil entering an eye would tend to be focused on the retina. Somewhat diffidently, he suggested an answer in a geometrical formulation which Bennett (1961) has shown to define the plane of the circle of least confusion.

Newton's writings on oblique astigmatism and other topics of geometrical optics are to be found in his *Optical Lectures*. These lectures had been delivered in Cambridge during 1669 but were not published until 1728, shortly after his death. In comparison with his *Opticks*, Newton's *Optical Lectures* are virtually unknown. As a result, a number of beautiful graphical constructions that ought to have passed into general currency have been allowed to pass into oblivion. It was the fate of even the greatest of Newton's contemporaries to be overshadowed by him. In respect to his *Optical Lectures*, Newton appears to have overshadowed himself.

It was Thomas Young (1773-1829) who picked up the threads left by Newton, similarly confining his published work to oblique astigmatism. Nowhere in Young's various writings on optics does he deal with refraction by cylindrical or other astigmatic surfaces. Nevertheless, he made considerable advances. In his Bakerian Lecture, Young gave the first description of an astigmatic pencil formed by oblique refraction. The diagram is not a schematic one but shows every sign of having been drawn from observation. The approximate focal lines and the circle of least confusion (termed by Young the 'circle of least aberration') are clearly shown. In addition, the equations given by Young correctly locate the circle of least confusion dioptrically (as distinct from geometrically) midway between the two focal lines.

Another of Young's contributions was a remarkable graphical construction that deserves to be better known. Consider the chief ray of a narrow pencil obliquely incident on a refracting surface. The following propositions are true for the sagittal and tangential meridians separately. First, to every point on the incident ray path, considered as an object point, there corresponds a unique image point on the refracted ray path and vice versa. In technical terms, the ranges of object and image points constitute a one-to-one correspondence. Second, the point of incidence, which is common to both the incident and refracted ray paths, is self-conjugate. It then follows from a theorem in projective geometry that a straight line drawn from any object point to its conjugate image point must pass through a fixed point termed the 'center of perspective.' Consequently, once this latter point has been located, we can find an image point by drawing a single straight line from the object point. For imagery in the sagittal plane, the center of perspective is easily shown to be the center of curvature of the surface. To find the center of perspective for the tangential section is a more formidable problem. Young solved it by means of a graphical construction which, though simple, is puzzling because it seems devoid of any optical rationale. It yields its secret only when approached from the standpoint of projective geometry (Bennett 1970).

Above all, Young made an especially valuable contribution to the study of astigmatism by relating it to the eye. First, he calculated the oblique astigmatism of the eye itself, plotting what we would now term the sagittal and tangential image shells after refraction at each surface. This procedure led him to the correct conclusion that the final image shells would normally straddle the retina, the curvature of which is therefore ideal from this standpoint. Second, in the course of the experiments described in his Bakerian Lecture he discovered that one of his own eyes was astigmatic, his optometer revealing a refractive error in the neighborhood of

$$-4.00/-1.75 \text{ ax. } 90$$

Since a further experiment with the same eye immersed in water showed no change in the astigmatism, Young concluded that it must be due to a tilt in the crystalline lens. He remarked that in his case an adequate correction could be obtained by tilting the spectacle lens. This was an expedient not unknown to the opticians of his day—an empirical remedy for a then mysterious condition.

It is well known that George Biddell Airy (1801-1892), who later in life became the Astronomer Royal, was the first person to correct astigmatism with a sphero-cylindrical lens. Having discovered his own left eye to be strongly astigmatic as well as myopic, he calculated the necessary radii of curvature and had a correcting lens specially made. In our modern notation its power would be approximately

$$-6.25/-4.62 \text{ ax. } 35$$

Airy gave an account of this historic step forward to the Cambridge Philosophical Society in 1825, but the volume containing his lecture did not appear until 1827.

Whether or not Airy was acquainted with Young's prior discovery of ocular astigmatism is open to conjecture, but there is certainly no doubt as to his outstanding mathematical skill. When William Hyde Wollaston (1766-1828) introduced his patented 'periscopic' lenses in 1804 he frankly admitted that he was unable to produce a rigorous theory to account for their superiority. In another paper published in 1830, Airy solved this problem and derived a mathematical expression showing the form in which a spectacle lens should be made in order to be free from oblique astigmatism. I have recently shown (Bennett 1965b) that this expression is mathematically identical (despite the different parameters and line of approach) with the formula deduced many years later by Tscherning (1904)—the basis of the well-known 'Tscherning Ellipses.' Airy's pioneer work in this field bore no fruit because it was too far in advance of its time.

Following Airy's pioneer effort in the correction of astigmatism, interest in the subject gradually spread. The French ophthalmologist Louis Emile Javal (1839-1907) became particularly interested and has left us a valuable review (Javal 1866) of the earlier researches and publications in this field.

So interesting and important a development could not possibly have failed to attract the attention of Donders. It was largely through his book on *Astigmatism and Cylindrical Lenses*, published in 1862 in Dutch, French, and German, that testing for astigmatism became an essential part of routine refraction.

After the basic principles had been established, progress was concentrated on finding improved methods and techniques for clinical use. One valuable device was the variable cylinder or 'Stokes lens,' named after its inventor Sir George Gabriel Stokes (1819-1903). Stokes was an Irish mathematician and physicist of great distinction, the discoverer of the phenomenon of fluorescence.

The original Stokes lens (Stokes 1849) was a combination of two plano-cylinders of equal and opposite power, one rotatable with respect to the other. When a Stokes lens is adjusted to give a desired cylinder power C, an unintended but unavoidable element of spherical power equal to $-C/2$ is also produced. This was originally considered a drawback but it it exactly what is required when cross-cylinder techniques are employed. The value of the Stokes lens as an aid to refraction was realized by Donders, Javal, and many others. A specially designed version of it was exhibited by Dennett in the USA in 1885, and another version designed as a trial-case accessory similar to the Risley prism was patented by De Zeng in 1908. We are also indebted to Stokes for the first mathematical analysis of obliquely crossed cylinders (1883). As he himself hinted and as Edward Jackson (1886) and others later showed in detail, the equations lend themselves to a simple geometrical solution on which the well-known parallelogram construction with doubled angles is based.

Much thought has been expended on the design of charts for the detection of astigmatism

...cation of its meridians. Sn ...n included several such charts in his complete set of ...yes. A particularly valuable cor ...bution was made by the St. Louis ophthalmologist John ...(1833-1913) who had spent a sh... time in Donders's clinic. In a paper delivered in 1878 ...scribed no fewer than 26 different ...igmatic charts. The majority were of his own design. ...ginal set of three first published in 1866 had received, as he himself put it, "a wide circula- ...ion." One of the later charts, which Green attributed to Noyes, foreshadows what later became ...own as the Maddox V. Interest in the design of astigmatic charts did not become exhausted ...with names such as Verhoeff, Maddox, Friedenwald, and Raubitschek would figure prom- ...ently. For a detailed review of this topic ...

...ile Javal, with the assistance of Schiotz, launched the first keratometer for clinical use ...the new instrument was welcomed as an aid to the determination of astigmatism. It was ...from the outset that the keratometer findings would have to be treated with some reserve ...Even if they could be accepted as a reliable indication of the total corneal astigmatism, they still ...take account of lenticular astigmatism. Moreover, the lens-eye separation introduces cylinder ...transposition complications, especially when a strong spherical correction is also needed.

...With these considerations in mind, Javal made a study of case records to see if there was ...any statistical relationship between the corneal astigmatism, as revealed by the keratometer ...reading, and the cylinder C found by refraction. By adopting the convention that positive ...cylinders are with the rule and negative cylinders against the rule astigmatism, we can express the relationship ...discovered—known as Javal's rule—by the equation

$$C = 1.25A - 0.75$$

...Later investigators arrived at very similar relationships, thus confirming the validity of ...Javal's as statistical generalization.

...Improved techniques of refraction inevitably led to the decline of the keratometer as a ...means of determining astigmatism. The most notable advance in this field was doubtless ...the invention of the cross-cylinder technique by Edward Jackson (1856-1942). His first published ...reference to it was made in a paper (Jackson 1887) devoted to a description of a small-aperture ...trial lens set which he had designed. The cross cylinder was mentioned, almost in passing, as an ...accessory to be used in finding or checking the cylinder power required. Twenty years elapsed ...before it was realized that the cross cylinder can also be used to refine the cylinder axis. It is ...interesting that Jackson himself was the first to make this discovery. Today, the cross-cylinder tech- ...nique is probably the most widely used of all in routine subjective refraction.

In many refractor heads the cross cylinder is mounted so far from the subject's eye that ...magnification effects and scissors distortion may become disturbing and impair the sensitivity of ...the test. A modified form of the cross cylinder, termed 'homokonic,' designed to overcome these ...drawbacks, has been described by Haynes (1958).

The Subjective Optometer

Current subjective refraction techniques require the use of a distant test object and a large ...assortment of lenses to form an image of it in the far-point plane of any given subject. An earlier ...arrangement was to use a near test object and vary its distance from a fixed lens to position the ...image in the desired location. This is the principle of the simple optometer. Since only one lens ...is required, it may be thought appropriate that a Scottish physician, William Porterfield (d. 1768), ...was responsible for the introduction of the instrument as well as for its name. In fact the optom- ...eter as described by Porterfield in his *Treatise on the Eye* (1759) did not even require a single lens. ...In essence, it was a device for locating the far point of a myopic eye by means of a movable test ...object (a vertical line), a Scheiner disk with two vertical slits was employed as a criterion of focus- ...ing.

The main substance of Porterfield's *Treatise* was contained in an earlier "Essay concerning ...the motions of our eyes," which had appeared in two parts in Volumes III and IV, respectively,

of a compilation entitled *Medical Essays and Observations*. Several editions of this work, published by A Society in Edinburgh, appeared from 1737 onwards but Porterfield's Essay contains nothing on the subject of his optometer that is not to be found in the later *Treatise*.

Porterfield's optometer was greatly improved by Thomas Young, who retained the Scheiner slits as an essential feature. The test object was replaced by a line engraved centrally along the length of the optometer bar. Viewed through the slits it would appear in the form of an elongated letter X; the perceived point of intersection of the two oblique lines was free from doubling and hence conjugate with the retina. To deal with hypermetropia he made the instrument reversible and added a +10 D lens at one end, providing various scales by which a direct reading could be obtained in terms of the code number (according to a system then in use) of the appropriate spectacle lens.

Young's optometer was described in his famous Bakerian Lecture to the Royal Society delivered in 1800 (Young 1801). With characteristic insight he pointed out that involuntary accommodation would often affect the result and suggested that "a power two or three degrees (intervals) lower than that which is thus ascertained will be found sufficient for ordinary purposes." Young also recommended that the eye not under test should not be closed but merely occluded.

A fascinating account of the use of a Young's optometer was given by J. Isaac Hawkins (1826), an English engineer. He had decided that he needed trifocals and must test his own eyes. Accordingly, he built himself an optometer from Young's description of his own model, using printed music staves as a test object so that he could detect the presence of astigmatism. By this simple means, Hawkins arrived at a distance prescription which in our notation, suitably rounded off, would be

$$R + 1.62/-0.62\times V$$
$$L + 1.25/-0.12\times H$$

He then designed, and had made by a somewhat reluctant optician, a pair of trifocals of Franklin construction, each portion accurately centered and independently angled so as to be approximately normal to the line of sight. Hawkins's name is fairly well known as the originator of trifocals, but his remarkable feat of self-refraction and numerous shrewd comments deserve much wider recognition than they have hitherto received. It is possible that Hawkins was not even acquainted with Airy's work on the subject, which had not then been published.

In 1876, by which time the trial case was in common use, the optometer was further improved by the French ophthalmologist Jules Badal (1840-1929). He moved the lens forward so that its second principal focus coincided with the spectacle point, approximately at the eye's anterior focal point. In this setting the optometer is positioned to record the spectacle refraction.

Two considerable advantages are afforded by the Badal system. First, the power scale of the instrument becomes linear. Second, the apparent size of the image of the test object remains very nearly constant whatever the subject's refractive error.

Badal used a +16.00 D lens, for which power the necessary travel of the test object is very nearly 4 mm per diopter. The optometer scale gave readings in this then very new unit of lens power, its range being from +15 to -20 D. A stenopaeic slit was incorporated in the eyepiece for use in cases of astigmatism. One of the test objects used in this optometer was a photographic reproduction of one of Snellen's optotypes, which made it possible to use the instrument also for visual acuity determination.

A few useful improvements were later introduced by Parent (1879), one of the pioneers of retinoscopy. He added a diaphragm in the eyepiece to sharpen the image formed by the +16 D lens, and a more suitable test object for dealing with astigmatic eyes. To reduce the stimulus to accommodation, Parent also constructed a binocular model.

Towards the end of the 19th century, subjective optometers were greatly in vogue and numerous different designs were put forward. There was even a suggestion that the trial case might become obsolete. In fact, it is the simple optometer which has been rendered obsolete (except for domiciliary use) by refinements in refraction routines employing trial lenses.

Nevertheless, the Badal principle retains its importance and has been utilized in the design of more sophisticated objective instruments.

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The Ophthalmic Trial Case

Although the transition from a range of trial spectacles to a set of individual trial lenses is a simple one technically, it marks an important advance in the development of optometry. Broadly speaking, it reflects the transition from selection to prescribing.

The basic idea seems to have occured independently to a number of practitioners during the first part of the 19th century. Priority is generally given to the German physician, G.T.C. Fronmüller (1843), who published a detailed description of the trial case he had designed for his own use. It was in this article that he uttered his famous denunciation of bifocals as "a certain means of ruining even the best of eyes." Our amusement at this dictum should perhaps be tempered by the reflection that some degree of caution is no bad thing in a medical man.

Writing in a Soviet ophthalmological journal, Magil'nitsky (1956) recently claimed priority on behalf of Professor I. Grubi, who had designed a trial case for use at the St. Petersburg Academy of Military Medicine as early as 1830. Even this claim can be disputed, because a description of a trial lens set and an adjustable trial frame is given in a highly interesting paper published by Du Bois (1826) in a Prussian technical journal.

Subsequent developments in the design of trial case lenses are reviewed in detail in Chap. 3. The evolution of the refracting unit is also traced in that chapter.

Spectacle Lens Numbering and Measurement

Through the centuries, many lens-numbering systems have been used, some arbitrary and others related to a measurable quantity such as focal length or radius of curvature. The focal length has the advantage that it can be measured directly in the simplest possible way, at least in the case of converging lenses. On the other hand, the concept of lens power—the ideal basis for a lens-numbering system—is almost intuitive and the reciprocal relationship of lens power to focal length is not difficult to perceive.

It is therefore not surprising that a lens-numbering system based essentially on power was described as early as 1623, in the first book devoted to spectacles, *Uso de los antojos* (The Use of Spectacles). Its author, Benito Daza de Valdés (1591-1634), was a notary attached to the Holy Office. The original work, published in Seville, is exceedingly rare, but a French translation, first printed in 1627, was republished by Albertotti in 1892. This made the work more widely accessible. Then, to mark its tercentenary, a facsimile of the original Spanish edition was published in Madrid under the editorship of Manuel Márquez in 1923.

According to the system described by de Valdés, the strength of a lens in *grados* (literally, degrees) was defined by a number denoting the reciprocal of its focal length measured in *varas*. (The *vara* was a Spanish unit of length, now obsolete, equivalent as far as one can tell to 0.83-0.85 meter.) In round figures, the power of a lens in *grados* would be 1.2 times its power in diopters.

A feature of exceptional interest in this book is the description of a simple means of measuring the power of a lens. It is highly probable, as von Rohr (1918) has suggested, that de Valdés did not invent the method himself but obtained it from an Italian source. A flourishing glass and spectacle-lens industry had already been established for some centuries on the island of Murano in the Venetian lagoon. Whatever the truth of the matter, it is to de Valdés that our thanks are due for having placed the method on record.

It requires the use of a number of specially prepared charts, one of which, intended for minus lenses of power 2 to 10 *grados*, is reproduced as Fig. 2–4.

Having placed his eye at the specified viewing distance—two-thirds of a *vara* (approximately 56 cm)—the examiner holds the lens to be measured over the right-hand circle marked *L*. He then withdraws the lens towards his eye until the image of the circle seen through the lens appears of the same size as the left-hand circle *S* viewed directly. The distance of the lens from the circle is then measured; the scale reading at this distance from the center of the star marking the zero point gives the power of the lens in *grados*. This method is optically sound. Let

p = (positive) distance in mm from test object to viewing point

q = (positive) distance from test object to lens when in position of equality

k = ratio of diameter of circle L (viewed through the lens) to that of circle S viewed directly

F = power of lens in diopters

Then it can be shown that

$$q = (p/2) - \{(p^2/4) + [1000p(k - 1)/F]\}^{1/2}$$

The distance q should be measured to the first principal point of the lens. The viewing distance is not critical.

Since the laws of conjugate foci were not known when de Valdés's book appeared, the scales could only have been calibrated empirically; but calculation shows that the graduations are, on the whole, remarkably accurate. The complete set of scales permits measurement of both plus and minus lenses up to a power of 30 *grados*.

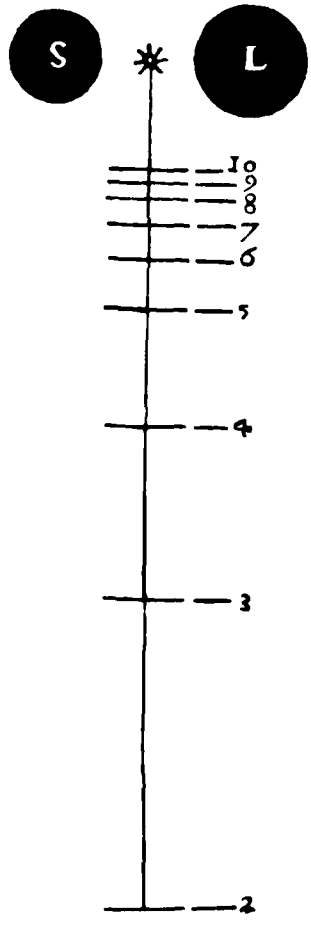


FIG. 2–4. One of a set of scales used by Daza de Valdés (1623) for the measurement of lens powers. (About four-fifths of original size.)

The method could easily be embodied in a simple piece of apparatus in which the lens is mounted on a sliding carriage, which would permit a direct reading. Various other refinements readily suggest themselves.

After this early manifestation, the notion of a numbering system based on power did not re-emerge until the 19th century. A firm theoretical basis was then laid by J.F.W. Herschel (1792-1871). In the article on 'Light' which he contributed in 1827 to Vol. IV of the *Encyclopaedia Metropolitana*, a masterly exposition of both physical and geometrical optics, he developed the latter on the basis of power, curvature (reciprocal of radius of curvature), and what he called 'proximity.' Defined as the reciprocal of the distance of one point from another, this term is the equivalent of our modern 'vergence.' Herschel derived the law of conjugate foci in the form

$$I = F + D$$

which corresponds to our

$$L' = L + F$$

Herschel's expression for the back vertex power of a thick lens would be recognizable almost on sight by a present-day student of optometry.

By the time Donders's classic work appeared in 1864, the world's leading ophthalmologists were ready to adopt a power numbering of spectacle lenses, but they seriously disagreed about the unit of power. Javal and others favored a lens of 240 cm focal length as the basis of numbering, a proposal that commanded a great deal of support at one time. However, it was vigorously opposed by Albrecht Nagel (1833-1895) and Monoyer, who advocated the meter as the unit of focal length and its reciprocal as the measure of power. Writing in *Annales d'Oculistique*, Monoyer (1872) addressed a personal appeal to his compatriot Javal of such eloquence and cogency that Javal changed his mind. Donders, too, was persuaded. It is altogether appropriate that our present lens-numbering system was formally adopted in 1875, the year in which the Meter Convention took place. The name given to the new unit of lens power, *the 'dioptrie,' had been suggested* by Monoyer a few years previously.

Adoption of the dioptric system of lens numbering did not completely solve the problem. At that time the 'power' of a lens would be generally understood to mean its equivalent power, the reciprocal of the equivalent focal length in meters. Unfortunately, the equivalent focal length is measured from a theoretical axial point which is not easy to locate. Apart from this practical objection, it is now self-evident that the back vertex power is the really significant quantity because, taken in conjunction with the vertex distance, it completely determines the effective power of any lens at the eye (in distance vision).

To the best of my knowledge, it was Badal (1883) who first advocated the back vertex power as the most convenient and logical basis for spectacle lens numbering. Some five years earlier, in 1878, Badal had described a simple lens measuring instrument—the Badal phakometer—for recording the back vertex power. As with the modern focimeter, the back vertex of the lens under test was placed at the anterior focal point of a built-in lens. The power scale thus became linear and the image seen by the examiner remained of constant apparent size, whatever the power of the lens under test. In essence, the optical system of Badal's phakometer is that of the modern focimeter with the light path reversed. Contrary to popular belief, the modern focimeter was not the work of Carl Zeiss of Jena. Its original inventor appears to have been C. J. Troppman of Chicago, who was granted U.S. patent No. 1 083 309 in 1914. Nevertheless, it is to the Carl Zeiss concern and their scientific director, Moritz von Rohr (1868-1940), that we are indebted for the first realization of back vertex numbering by a large manufacturer. Their computed series of Katral and Punktal lenses, introduced shortly before 1914, were all made to a back vertex numbering which eventually became an internationally accepted system.

Incidentally, in the same article in which he advocated a back vertex numbering, Badal discussed the question of spectacle magnification, taking the form and thickness of the lens into account. His conclusions are entirely in line with the modern presentation of the subject, apart from the fact that he took the eye's nodal point instead of the center of the entrance pupil as his

point of reference. Badal correctly analyzed spectacle magnification as the product of two components which we now term the 'power factor' and the 'shape factor.' Moreover, his expressions for these two factors are essentially in the form in which they are presented in current textbooks. In all, Badal's contributions to optometry seem to have missed the recognition they deserve.

Objective Methods of Refraction

An objective method of refraction is one in which the examiner substitutes his own opinions for the patient's. This classic definition is largely true of the earlier methods in which the skill, experience, and judgment of the practitioner play a decisive role.

Skiascopy—or retinoscopy, as it is invariably termed in Great Britain and certain other countries—is the oldest and still, perhaps, the most widely practiced method of objective refraction. It was an offshoot from ophthalmoscopy. Sir William Bowman (1859) described how he utilized the shadow movements produced by rotating his ophthalmoscope mirror to detect slight degrees of keratoconus. As later reported by Donders, Bowman used the same technique to detect the presence of astigmatism and to locate its principal meridians. At that time, Bowman was an ophthalmic surgeon at the Royal London Ophthalmic Hospital, later to become known as Moorfields Eye Hospital.

However, it is to Ferdinand Cuignet (d. 1889), a French ophthalmologist, that we are indebted for rediscovering the technique and developing it into an objective method of refraction. He termed it keratoscopie—a name which, like several others coined by later writers, betrays a certain misconception as to the true nature of the pupillary reflex. Cuignet expounded his new technique of refraction in a series of papers in *Recueil d'Ophtalmologie*, the first in 1873. They were difficult to follow and it was largely through the efforts of Cuignet's junior colleague Mengin that the leading French ophthalmologists of the day were induced to study the new technique. Thanks to the work of Mengin, Chibret, and especially Parent and Landolt, skiascopy was quickly placed on a firm theoretical basis.

Candles or oil lamps were the original sources of illumination. The first self-luminous instrument was shown at Heidelberg by Hugo Wolff (1896), but the simple pierced mirror, plane or concave, persisted for many decades.

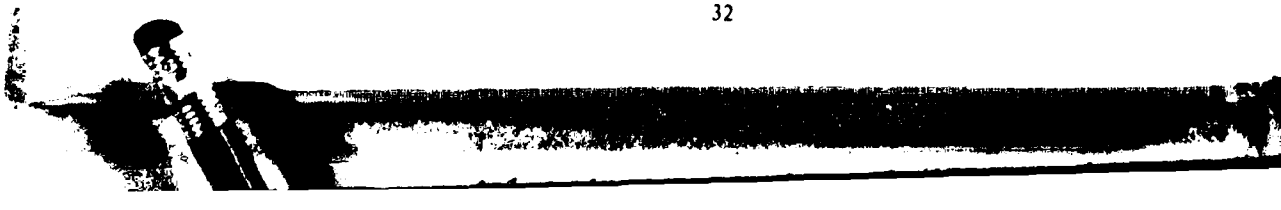
Several important variants of the original method have established themselves from time to time. Streak skiascopy was another innovation by Wolff, who demonstrated the instrument he had designed for this purpose at the Heidelberg meeting of 1900. In the USA, interest in the technique was re-awakened by Jacob Copeland (1927), the designer of a streak skiascope.

Dynamic skiascopy was the creation of Andrew Jay Cross (1855-1925), an American optometrist and university lecturer. The method was described in his first book, published in 1903, but a more authoritative exposition is to be found in a later work that appeared in 1911. The year previously, Cross had obtained a U.S. patent (No. 978 276) for the dynamic skiascope illustrated in Fig. 2-5. It incorporates two fixation targets, one in front of and the other behind the plane of the mirror. Incidentally, the technique of asking the patient to "count the dots" is not of recent origin, as I had at first supposed, but was originated by Cross himself. In fact, Cross suggested the further stratagem of disputing the patient's count so as to maximize his attention.

Another interesting variant attributed to Strampelli and before him to Gullstrand was taken up and described in more detail by Rosengren (1948). In this method, a direct ophthalmoscope is employed to send light into the patient's eye, with the axis of illumination slightly displaced from the axis of observation. The mirror is not rotated. In the 'reversal' condition, the subject's pupil appears to be uniformly illuminated but the presence of only a small amount of ametropia will displace the reflex, so that a shadow appears in one part of the pupil.

A more recent development, "cylinder dioptometry," was described in 1970 by its originator, Dr. Nathan Ben-Tovim, of Tel-Aviv. The new technique, which is claimed to be extremely sensitive, requires the construction of a special piece of apparatus which is, however, not unduly complicated.

Other objective methods of the nonautomated type under discussion are embodied in the various forms of the optometer described in Chap. 3.



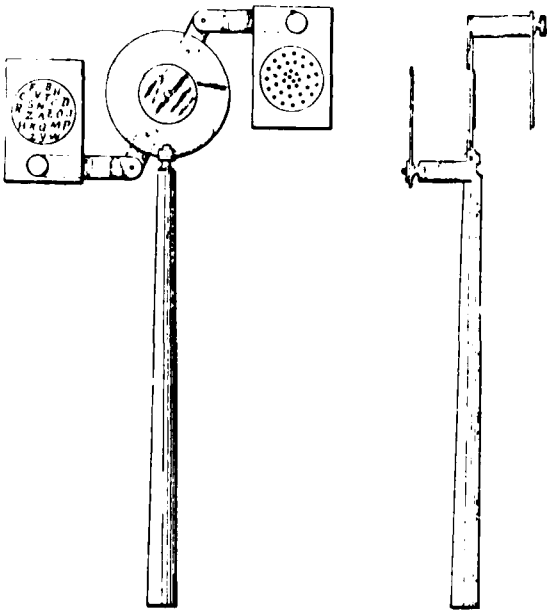


FIG. 2-5. The dynamic skiascope patented in 1910 by A. J. Cross.

Automated Refraction

An objective optometer can be considered as automated when the operator's role is merely to insure that the patient does what he is told. Such an instrument is doubly objective, inasmuch as neither the operator's nor the patient's judgment is called into play.

Possibly the first instrument to satisfy these criteria was the "electronic refractionometer" patented by Geoffrey Collins (1939), an English optometrist, and described in a paper he published in 1937. A prototype exhibited in London at that time aroused great interest. Unfortunately, further development was stopped by the outbreak of war in 1939 and was never resumed. Nonetheless, in many of its essential features, including the use of an infrared light source, the Collins instrument anticipated several of the objective optometers developed in the postwar period.

Some degree of automation may be applied to subjective refraction as well. In general, an ophthalmic prescription contains three elements—sphere, cylinder, and axis direction—so that it should theoretically be possible to deduce the prescription from no more than three relevant pieces of information. For example, the refractive state of the eye could be examined in three arbitrarily selected meridians, by means of only spherical lenses. Under the stimulus of a short but thought-provoking paper by Westheimer (1957), Bennett (1960) expounded a possible basis for such a technique.

In brief, the patient views a distant line through a Scheiner disk with the orientation of the holes perpendicular to the line. If doubling is perceived, it is eliminated by suitable adjustment of a device that produces continuously variable spherical power. This maneuver is carried out in three different meridians; the simplest set to handle mathematically is vertical, horizontal, and 45°, in any order. If the three spherical powers recorded in these meridians are denoted respectively by V, H, and M, it was shown that the prescription was deducible from the following sequence of equations:

$$\text{Axis direction } (\theta) = 0.5 \text{ arc tan } \frac{2M - (H + V)}{H - V}$$

$$\text{Cylinder power } (C) = \frac{H - V}{-\cos 2\theta}$$

$$\text{Sphere power } (S) = \frac{H + V - C}{2}$$

Two special cases, in which at least one of the above expressions becomes indeterminate, require attention. First, if the ametropia is purely spherical we have $H = V = M = S$.

Second, if $H - V = 0$, then $\theta = 45°$, $C = 2(H - M)$, and $S = M$.

Another method of dispensing with rotatable cylinders, which has several advantages including that of utilizing the full pupil, is incorporated in the Humphrey Vision Analyzer Model 210 and is described in various patents (Humphrey 1974, 1975, and 1976). In brief, the cylindrical correction required is supplied by two variable-power astigmatic lens units, each separately adjustable so as to produce the effect of a Stokes lens or cross cylinder of any desired power. In such a lens, the powers along the two principal meridians are equal but opposite in sign and the mean is thus zero.

The two astigmatic units are mounted close together in fixed orientations. One has its plus and minus axes at 0° and 90° (or vice versa) and the other at 45° and 135° (or vice versa). It may be shown mathematically that in any state of adjustment the combination is optically equivalent to a single cross cylinder, the power and orientation of which are determined solely by the strengths of the two components. A third lens unit provides variable spherical power.

A simple routine of refraction has been devised whereby, after the spherical power has been adjusted to give best vision of a vertical line, the cross cylinder at axes 45° and 135° is adjusted to bring this line into sharp focus. A line at 45° then becomes the test object for setting the other cross cylinder with its axes at 0° and 90°, again after any necessary adjustment of the spherical power. A microcomputer performs the necessary calculations so that the readout can be presented in the conventional sphero-cylindrical form of lens prescription.

Pre-computer Aids to Calculation

Of all the various aids to optometric calculation preceding the modern computer, two main kinds demand attention: specially designed sliderules and nomograms.

Numerous optical sliderules varying in purpose and scope have been produced from time to time. The earliest known to me was devised by Javal (1865). At that time, in France, spectacle lenses were numbered by focal length in Paris inches. It required quite an effort to determine, for example, the lens equivalent to a combination of a -3½ and a -24 inch. Javal's sliderule not only gave an immediate solution to such problems but by an ingenious choice of scale factors also dealt equally simply with problems involving prismatic effects and ocular convergence. A separate scale, based on the data that had recently been published by Donders, coped with problems concerning amplitude of accommodation and the choice of reading glasses.

Another sliderule of particular interest, designed by Professor Rochat, was introduced in the 1930s by Carl Zeiss of Jena. Its main purpose was to solve problems relating to effectivity—for example, conversion from spectacle to ocular refraction (or vice versa), compensation for vertex distance changes, and so on. Tapered off at one end to a rounded tip, the sliding bar served also as a depth gauge, giving readings on a vernier scale to the nearest 0.1 mm. By this means the vertex depth or 'sag' of the concave back surface of a lens could be measured directly, thereby simplifying the measurement or calculation of vertex distances. A detailed description of the Zeiss sliderule, together with many worked examples illustrated photographically, was given by Theo. E. Obrig (1935).

A sliderule of considerable scope and ingenuity, comprising 12 scales in all, was described by its designer, Tien-Yung Miao, in 1945. In his paper, published in English, the author states that his sliderule had been successfully employed for more than two years at the Institute of Aviation Medicine in China.

Nomography was the creation of French mathematicians, notably Maurice d'Ocagne, whose classic treatise on the subject appeared in 1899. A nomogram is a graphical representation

of a mathematical equation. In its simplest form it reduces to a doublesided scale. The most common type of nomogram embodies a formula containing three variables, each represented by a separate graduated scale. A cursor or index line laid across the points representing known values of two of the variables intersects the remaining scale at the point giving the required value of the third (unknown) variable.

Many nomograms in the optical and optometric fields have been published at various times and Bennett (1948) has perpetrated a few of his own. A typical example, hitherto unpublished, is shown in Fig. 2.6.

It is well known that the true effort of ocular accommodation that has to be exerted when an ametrope views a near object through distance-correcting spectacles is not the same as the so-called 'spectacle accommodation,' which is simply the dioptric equivalent of the object distance from the spectacle plane. In general, myopes need to accommodate less and hypertropes more than the spectacle accommodation. If a spectacle lens of typical form and thickness is assumed, the relationship between the ocular accommodation A_o and the spectacle accommodation A_s is given to a reasonable degree of accuracy by the approximation

$$U = A_o/A_s = 1 + 0.002dF_v'$$

in which d is the vertex distance in mm and F_v' the back vertex power of the distance-correcting lens. Over the range of powers +8.00 to −10.00 D, the error due to the approximation nowhere exceeds 5 per cent.

J. I. Pascal (1952) made a valuable contribution to the study of this subject; he termed the ratio U the "accommodative unit." Multiplied by the spectacle accommodation, the accommodative unit gives the true ocular accommodation required.

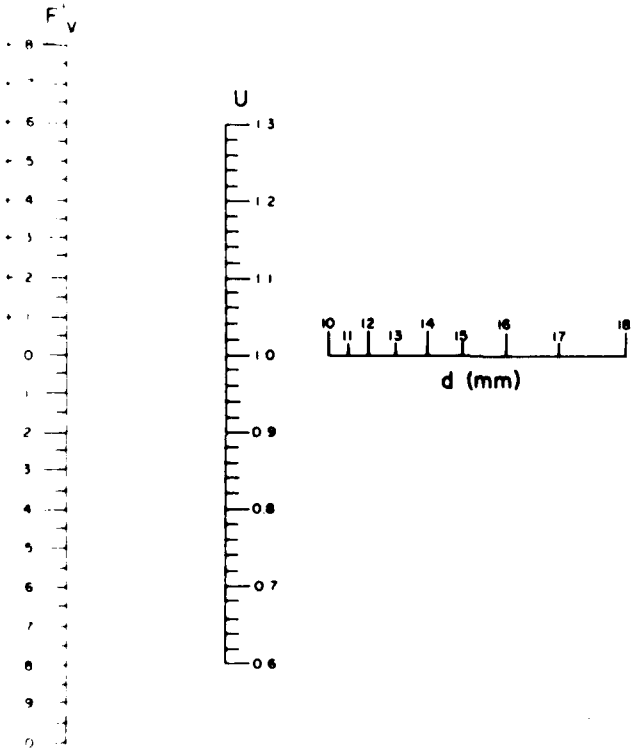


FIG. 2.6. Nomogram of the approximate formula $U = 1 + 0.002dF_v'$ connecting the power F_v' of the distance-correcting lens, the vertex distance d (in mm), and the 'accommodative unit' U.

Figure 2-6 is a nomogram of the above formula. Suppose F_v' to be -8.00 D and d to be 13 mm. A cursor or straightedge placed across these points would be found to intersect the L scale at approximately 0.79. Hence, to read at one-third of a meter (A_s = 3.00 D), the ocular accommodation required in this case would be 3.00×0.79 or approximately 2.37 D. Thanks to effectivity, a built-in reading addition of 0.62 has been provided.

In effect, the nomogram replaces a set of tables. Its economy and elegance appeal to the mathematical mind, but, like the sliderule, it is threatened by the rising* tide of computers.

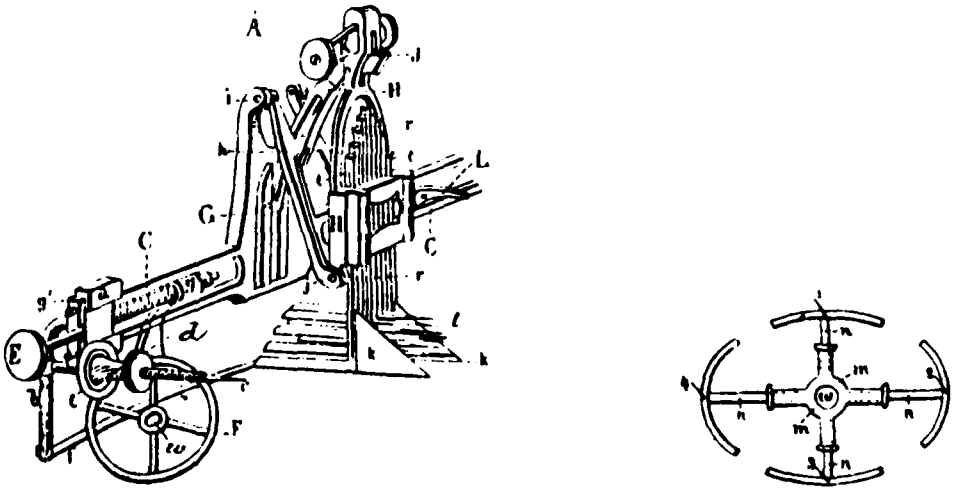
Facial Measurements for Frame Fitting

An old patent (No. 397 744) granted in 1889 to E. B. Meyrowitz and C. E. Dressler is worthy of mention here because its object is the automatic recording of facial measurements for frame fitting. Though the means employed are potentially hazardous, they are not lacking in ingenuity.

The main features of the device are illustrated in Fig. 2-7, in which (a) is an adjustable frame with curlside temples (not shown in the drawing). The complicated bridge assembly is pivoted at the top so that the projection can be varied. A set of vertically sliding rods, the lower ends of which are turned through a right angle towards the patient, automatically adjusts itself to the patient's nasal contour. To facilitate determination of a suitable lens size, an expanding lens gauge, shown in more detail in (b), is mounted on each side of the frame. Each is separately adjustable so that its center can be placed in any desired position relative to the pupil.

Pins or needles—both terms are used in the patent specification—projecting forward toward the operator are attached to the center and extremities of each principal axis of the lens gauge, to each of the sliding rods of the bridge assembly, and to adjustable members at the right and left ends of the frame. In addition, a vertical triangular blade pointing forwards is mounted on each side of the bridge assembly. When the frame has been satisfactorily adjusted and the various movable parts locked in position, it is returned (points uppermost) to its specially

*But inevitable (Ed.).



(a) (b)

FIG. 2-7. Essential features of the measuring device patented by Meyrowitz and Dressler (1899): (a) general view (in part) of the front; (b) more detailed drawing of the expanding lens-gauge.

designed container, in the lid of which one or more printed cards have been previously positioned. The lid is then closed. When the box is re-opened, a series of pinpricks will be found on the card(s), recording temple width, lens dimensions and distance between centers, and nasal contour. In addition, the bridge projection is given by the length of the vertical slits cut by the triangular blades.

It is not wholly inconceivable that the principle of this device may find some future embodiment in a more sophisticated form.

Acknowledgments

Every writer on historical and scientific topics can profit by the labors of his predecessors. In the fields of physiological optics and spectacles, the numerous papers by von Rohr, Greeff, Boegehold, Pergens, Barnett, and others are invaluable sources of information. Nevertheless, recourse to the original literature is indispensable if fresh interpretations and discoveries are to be made. I have consulted all the works and papers cited in this review and therefore accept responsibility for any misstatements or errors of interpretation. If any such are discovered, I should be grateful for having them brought to my notice.

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Chapter 3
OPTICAL SYSTEMS FOR THE REFRACTIVE EXAMINATION OF THE EYE

Maxwell M. Lang

ONE HUNDRED AND FIFTY years ago neither the eye refractor nor the trial lens set had been invented. Although the use of loose trial lenses was mentioned nearly 300 years ago, it was really Donders who systematized the trial case and trial frame. Some of the first lenses used for ophthalmic purposes were numbered according to the radius of curvature of the optical lap on which they were ground and polished. These early lenses were symmetrical, having surfaces of equal curvature. Indeed, it would have been impractical to have manufactured them in any other form considering the magnitude of their aperture. Since the glass commonly used in their manufacture had a refractive index of approximately 1.5, the radius of curvature of the optical lap used for each of the equi-biconvex or equi-biconcave lenses was very nearly equal to the focal length of the lens. In this system, measurement was in inches and the strength of each lens was expressed as the reciprocal of the focal length in inches or the lens number. Thus, a number 20 lens of 20 inches focal length was assigned a strength of 1/20. A major disadvantage of this system was that the lens numbers decreased with increasing power (Emsley and Swaine 1951, Rochester 1915, Landolt 1886).

This method of numbering created a problem when, as frequently is the case, trial lenses were used in combination. Even assuming that such combinations may be treated as if they were thin lenses in contact, calculations involving the algebraic addition of awkward fractions were often involved in order to evaluate the strength and hence the focal length of each prescription lens. Further objections to the original system of numbering were variations in the length of the standard inch in different countries and the irregular intervals of such a series.

At the suggestion of Monoyer (1872) and Nagel, the dioptric or metric system of numbering lenses was adopted. All the objections to the earlier method were at once eliminated. The focal lengths were now measured as fractions of a meter. Lens strength was still defined as the reciprocal of focal length by a unit called the diopter. Eventually trial lens sets were manufactured from one-eighth diopter intervals in the low power range, to various multiples of one-eighth diopter intervals in the higher power ranges. Thus, incremented combinations of lens power in intervals of one-eighth diopter could be obtained by using lenses in series. The use of multiples of one-eighth diopter as a basic incremental unit of lens power immediately obviated the need for adding small fractions in order to obtain the final prescription. The number defining lens strength in diopters now increased with the strength of the lens and was therefore more directly related to the magnitude of the refractive error, whereas in the original system the reverse was the case.

Most of the early metric trial lenses were still of simple equi-biconvex and equi-biconcave design. Jackson (1887) seems to have made the first major departure from this procedure with a trial lens set in which all the spherical lenses were either of plano-convex or plano-concave form. The mounted lenses were 25 mm in diameter. He claimed that the use of plano-spherical lenses permitted more convenient combinations of lenses, a reduction in spherical aberration, and

better facilities for lens neutralization. A U.S. patent for a reduced aperture trial lens set was granted to Meyrowitz (1915).

In order to assess the magnitude of the refractive error, it was necessary to hold trial lenses in front of the patient's eye in some convenient lens holder. To do so may seem to be a very simple matter not requiring any special care, yet many different styles and shapes of trial frames have been made ranging from simple dual cell nonadjustable devices (Light weight, Fig. 3-1), and those supported by the head rather than the nose and ears (Californian, Fig. 3-2), to rather complicated fully adjustable multicelled frames and systems such as the De Zeng Refraction and Muscle Testing Apparatus (Fig. 3-2) and the Skioptometer (Fig. 3-4). The latter were undoubtedly forerunners of the modern eye refractor. The successful trial frames have been relatively comfortable to wear, have been manufactured from a light-weight alloy, and have permitted free adjustment of every variable. Jackson's trial frame (1887) weighed less than one ounce.

In 1912 Carl Zeiss introduced a series of lenses in which back vertex power was used as the system of lens numbering, as first advocated by Badal (1883). Once the virtues of this system were understood, back vertex trial sets began to appear. However, such sets were not additive and combinations of spherical and cylindrical lenses in series could produce results that were significantly different from the algebraic summation of the labelled powers of the component lenses.

The first attempt to produce a truly additive trial lens set is described in a U.S. Patent filed by G. A. H. Kellner on 9 October 1916 and awarded on 7 May 1918. The patent was assigned to Bausch and Lomb Optical Co., which produced the lenses under the name of Precision trial set. In this series Kellner used plano-convex and plano-concave spherical and cylindrical lenses of uniform aperture (15 mm) and center thickness (1.8 mm) throughout. The cylindrical lens mountings had milled edges but no handles. Thus their rotation in the cells of the trial frame was unobstructed. It was a necessary feature of the design that the cylindrical lens was always placed in front of the spherical lens in a specially designed twin-cell trial frame (Fig. 3-5). Later, two additional carriers were provided for supplementary lenses. The plano surface of one lens should face that of the other. This arrangement insured that the thickness of the air space between any cylindrical lens and any spherical lens of the series remained constant for all possible combinations. The powers of the cylindrical lenses were all computed to provide the prescribed dioptric effect at the back vertex or second principal point of each spherical lens. The range of spherical lens powers was from ± 0.25 to ± 20.00 diopters. Both spherical and cylindrical lenses were provided in intervals of 0.25 diopter up to ± 3.50 diopters. However, the intervals were reduced to 2.00 diopters for spherical powers in excess of ± 6.00 diopters. Since lens position was of vital importance in the theory of the design, such a wide interval is a serious limitation of the system (Lang and Marg 1975). Prentice (1917) in an appraisal of the Precision trial set writes with some affection on the merits, accuracy, and craftsmanship of it, and the pleasure he has had in correcting astigmatism with it. He also comments on the manufacturer's precaution of not only engraving the axes of the cylindrical components on the edges of the glass lenses themselves, but also on the edges of their carrier disks.

The next refinement in trial lens design was proposed by Tillyer in U.S. Patent No. 1 455 457, which was filed 5 September 1919 and awarded 15 May 1923. In many ways Tillyer's patent was a generalization of the Kellner system, as discussed in detail below. Tillyer showed that a set of additive vertex power trial lenses of nonplano form may be provided. He claimed that the following criteria only need be observed.

1. The cylindrical lens should be placed in front of the spherical lens if a sphero-cylindrical combination is required.

2. The distance of the back vertex of the cylindrical lens from the front vertex of the spherical lens must be held constant for all combinations of the series.

3. The front surface power and center thickness of all the spherical lenses of the series should be constant.

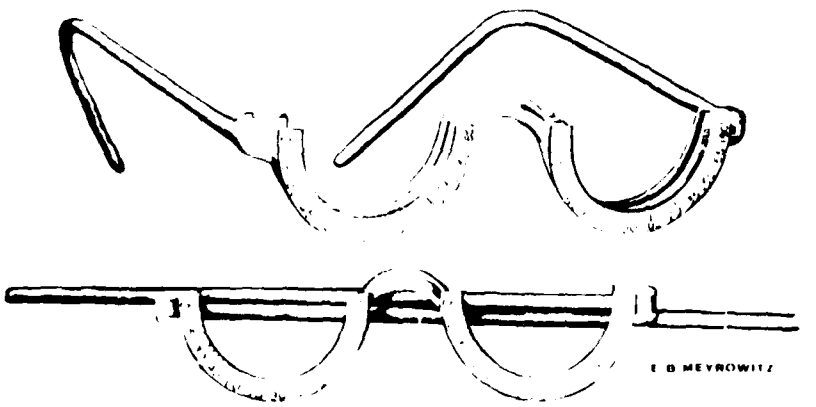


FIG. 3-1 The Light weight trial frame

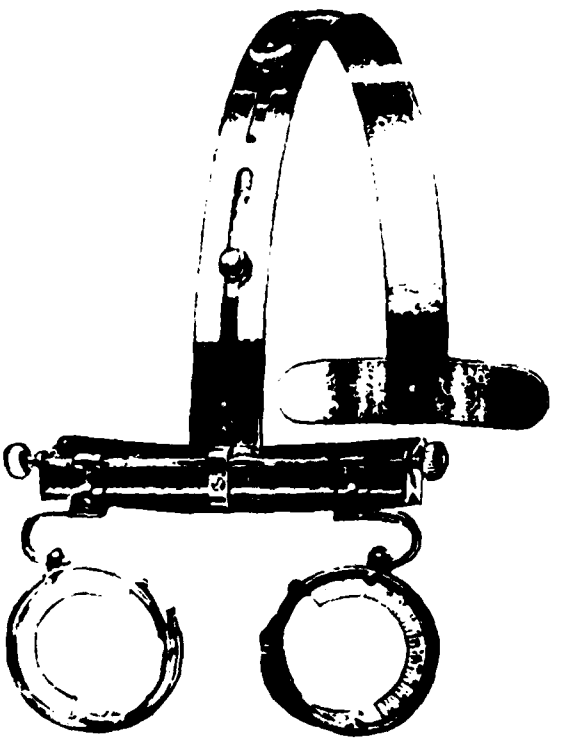


FIG. 3-2 The California trial frame, Baers

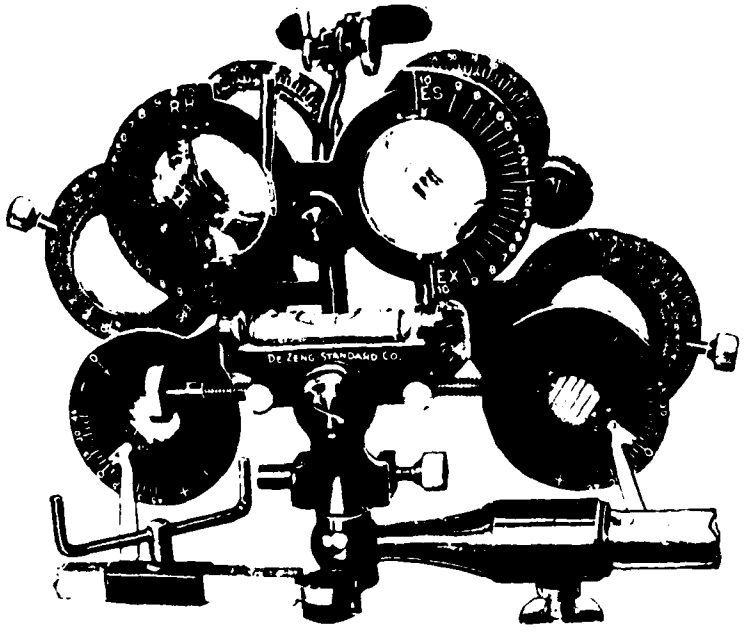


FIG 3-3 The De Zeng Refraction and Muscle Testing apparatus

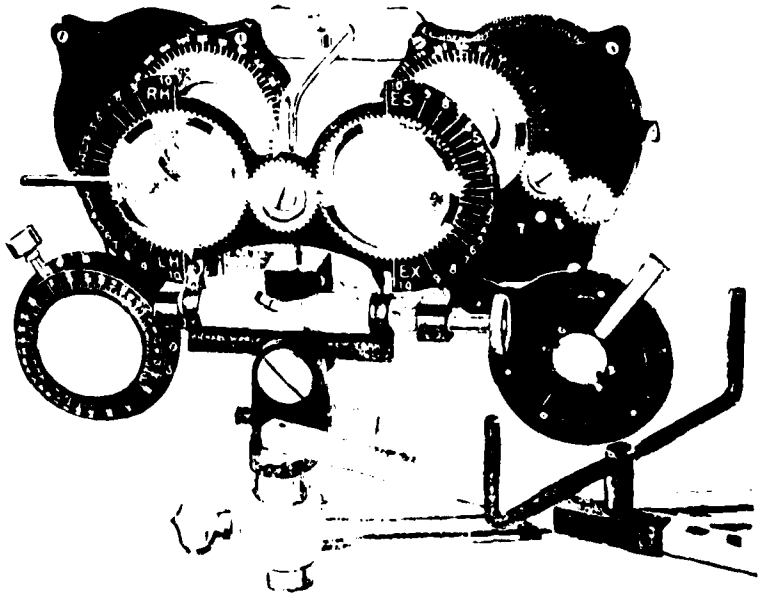


FIG 3-4 The Ski-optometer

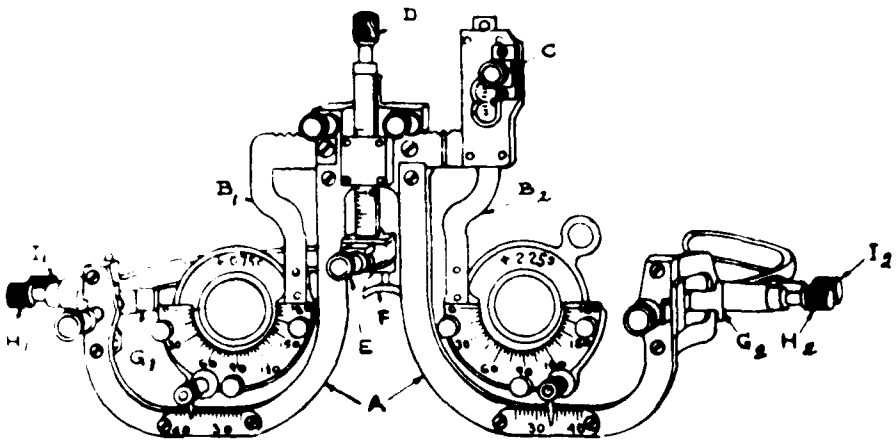


FIG. 3.5. The Precision trial frame.

[illegible] additivity is independent of the form of the cylindrical lens. It is surprising that neither Kellner nor Tillyer seem to have considered the work of Mayer (1909), in which he [illegible] trial lenses of different form having the same back vertex power are not necessarily [illegible] effective for near vision. Bennett (1966) clearly explains this principle and shows that [illegible] prescriptions synthesized with additive vertex power trial sets of the Kellner type are probably [illegible] likely to be replicated by ordinary spectacle lenses of corresponding power. This was [illegible] the view of a committee appointed in 1954 by the British Ministry of Health to [illegible] standards for trial case lenses. Their report was published in 1956 and stated that although [illegible] vertex power sets of the Kellner type do solve the problem of lens effectivity [illegible] usage, their performance for near use is often inferior to other systems. The committee did not comment on the Tillyer design but proposed that certain advantages would follow the adoption of the Kellner principle in reverse; that is, if the spherical lens were placed in front [illegible] cylindrical lens. The committee claimed that this procedure would insure that the effective [illegible] power of the combination was always correct for both distance and near usage and that [illegible] spherical lenses need not be of uniform thickness, larger lens apertures than those advocated by Kellner could be used. The Ministry of Health Committee on Trial Case Lenses also made recommendations on manufacturing tolerances for trial lens sets. These proposals were subsequently incorporated in British Standard No. 3162, Ophthalmic Trial Case Lenses (1959).

The optical firm of Rayner and Keeler Ltd. includes in its range of trial lenses an additive vertex power set with lenses of a 20-mm reduced-aperture type. It is claimed that both lenses and mounts comply with the requirements of the British standard mentioned above. The cylindrical lenses are mounted in standard 38-mm-diameter rims, whereas the spherical lenses are mounted in rims of 26 mm external diameter so that the cylindrical axis marking will not be obscured. Another feature of the Rayner and Keeler trial set is that the spherical lens mountings are of clear plastic with a convex spherical front surface, which serves as a magnifier for the axis markings on the cylindrical lenses. C. Davis Keeler Ltd. has also produced an additive vertex power trial lens set based on the Ministry of Health recommendations.

Swann (1939) described a trial case made to his specifications as the largest in the world, which is therefore worthy of mention for that reason alone. However, it did possess some other unusual features. It contained 411 lenses and disks. An electric heating element was fitted beneath the tray of lenses. The warmth from this unit removed any tendency for the lenses to fog on humid days. The lenses were of plano-spherical or plano-cylindrical form, and the latter were antrosted to indicate the axis direction. There was a spacing of 0.5 in. between the lens

slots in the tray to facilitate easy handling. Swann claimed that it was a rare occasion for more than one spherical and one cylindrical lens to be required for synthesizing a refractive correction.

Parallel to developments and refinements in the design of trial lens sets was the appearance of a variety of ingenious hand-held and stand-supported devices for measuring the refractive and accommodative powers of the eye. These instruments are called optometers, and have had a mixed reception. The term optometer seems to have been first used by Porterfield (1747). However, the research into optometers does represent an attempt to simplify or perhaps oversimplify the task of measuring ametropia. Optometers may be classified broadly into two main groups: subjective optometers, in which the result is substantially dependent upon the response of the patient; and objective optometers, in which the result is to a large extent independent of the patient's response.

Subjective optometers may be further subdivided as follows, according to the essential feature of their optical design.

a. The single convex lens.
b. The Galilean telescope.
c. The astronomical telescope.
d. The Scheiner experiment.
e. The chromatic aberration of the eye.

The Single Convex Lens

The simple optometer consists of a suitable test field, which may be moved along a rod or tube in front of a convex lens. The latter occupies the spectacle plane of the eye being examined. The test field is located in the anterior focal plane of the optometer lens in emmetropia. In myopia the test field must be moved closer to the optometer lens so that a divergent beam of light reaches the patient's eye as if it had originated from the patient's far point. In hypermetropia the test field should be moved in the reverse direction so that the light refracted by the optometer lens converges on the far point of the eye. In each case the movement of the test target may be used to determine the magnitude of the ametropia. The rod on which the test field moves may be calibrated for a direct readout of the result. Admirable as this simple device may appear to be in theory, the results obtained in practice are very unreliable, mainly owing to the patient's awareness of the nearness of the test field, which provides a very strong stimulus to accommodation. The single convex lens is the simplest means of varying the vergence of the beam reaching the patient's eye. It has been therefore used frequently in optometers. Coccius (1851), von Hasner (1851), Smee (1854), von Graefe (1863), von Burow (1863), Donders (1864), Laurence (1865), Badal (1876), Burchardt (1876), Sous (1881), and others have made use of this principle.

In order to overcome this defect of the simple optometer, a number of instruments were designed with an optical system that provided a retinal image of relatively constant size regardless of the position of the test field. It was hoped that such a system would not only obviate the stimulus to accommodation, but also avoid the recognition of blurred magnified images of the test field.

In arrangements due to Badal and to Burchardt, the second principal focus of the optometer lens coincides with the nodal point of the eye, an idea originally said to have been conceived by Nagel (Sr.). Thus, test objects subtend equal visual angles in the emmetropic and axially ametropic eye. However, it is easy to show that the retinal image in such systems becomes larger as the length of the eye increases. A more serious disadvantage of this arrangement is that the results are given in terms of nodal-point refraction rather than spectacle-point refraction. Badal's optometer (1876) consisted of a cylindrical tube about 30 cm long with an eye hole at one end. A convex lens of 63 mm focal length was fitted into the tube so that one principal focus coincided with the eye hole. Behind the lens a transilluminated test field could be moved along the axis of the tube by means of a rack and pinion, thus controlling the vergence of light leaving the optometer lens. The test fields were interchangeable and the optometer was mounted on an adjustable stand. The range of measurement of this instrument extended from

...15 to 20 diopters. If the optometer is arranged so that the second principal focus of the optometer lens coincides with the anterior focal point of the eye, as advocated by Badal, then a ray parallel to the principal axis of the optometer before refraction is parallel to the principal axis of the eye after refraction. In this arrangement of the Badal optometer the principle of equality of retinal image size is preserved, but the awareness of nearness of the object is substantially eliminated. The instrument scale is linear with such an arrangement.

An optometer described by Bull (1887) for rapid refraction was a hand-held graduated optical bench containing test targets and an astigmatic chart on a slide at one end and a complex eye piece consisting of three movable lenses at the other (Fig. 3-6).

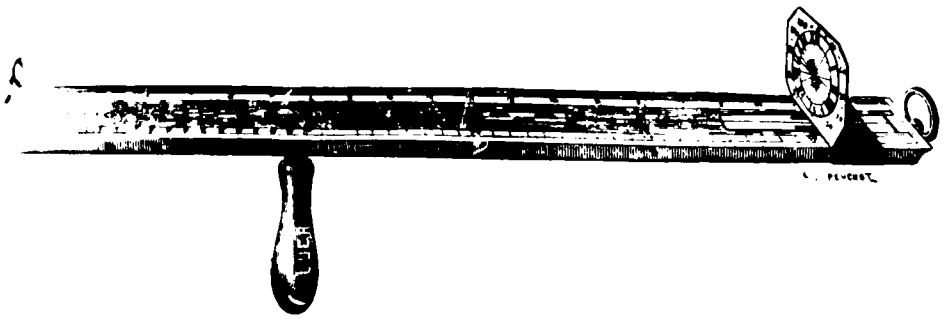


FIG. 3-6. Bull's optometer.

Burow's optometer (1863) consisted of a telescopic tube operating through a rack-and-pinion system. At the ocular end of the tube was a convex lens of 4 in. focal length; at the other end, a ground-glass plate containing test types.

Donders (1864) described an optometer based upon an invention of von Hasner (1851). It consisted of a board nearly 5 feet long and 9 Parisian inches wide. It was equipped with 3 grooves which were parallel to the long axis of the board. In these grooves, a wire optometer could be moved. The distance between the external grooves was just under 60 mm. If the wire optometer was moved along the middle groove both eyes contributed equally to the convergence. A recess was cut into one end of the board to accommodate the patient's nose. In front of his eyes were two lens holders. The head was supported by two adjustable rods on which the cheeks rested.

So broad were Javal's interests that it is not surprising that he also turned his attention to the design of optometers. One optometer resembled a Brewster stereoscope mounted on a stand. The target field was in the form of a stereoscopic plate comprising two circles with the distance between their centers corresponding to the interpupillary distance. One circle was divided into 30° segments by twelve radiating lines labelled I to XII. If the visual axes were parallel, the two circles were fused into a single percept. By means of a rack and pinion the target field could be moved away from the patient until just one radiating line remained distinct. The direction of this line corresponded to the meridian of highest refraction. Behind the optometer lens was a series of concave cylindrical lenses which were actuated by a system of planetary gears so that they could all be rotated into position in front of the eye at the same axis for measuring purposes. Javal is credited with a second optometer consisting of a disk of positive and negative cylindrical lenses ranging in power from 0 to 7 diopters. Both disks could be rotated on a common spindle and a planetary system similar to that described above was retained for axis control. The disks were each about 30 cm in diameter and the whole unit was mounted on a heavy castiron stand. This instrument was most certainly the predecessor of the modern eye refractor (Fig. 3-7a). This optometer was first described by Gavarett (1890).

Another novel device, and certainly one of the forerunners of the modern binocular eye refractor, was the optometer of Le Mehauté. This device was an attempt to displace the trial

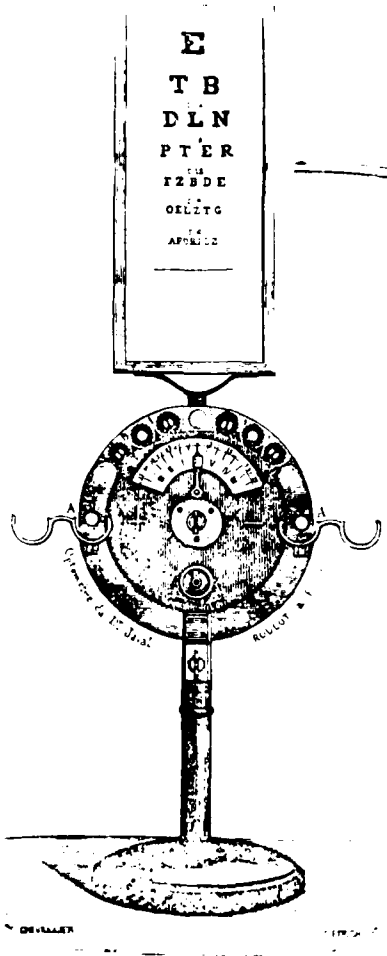


FIG. 3-7a. Javal's optometer.

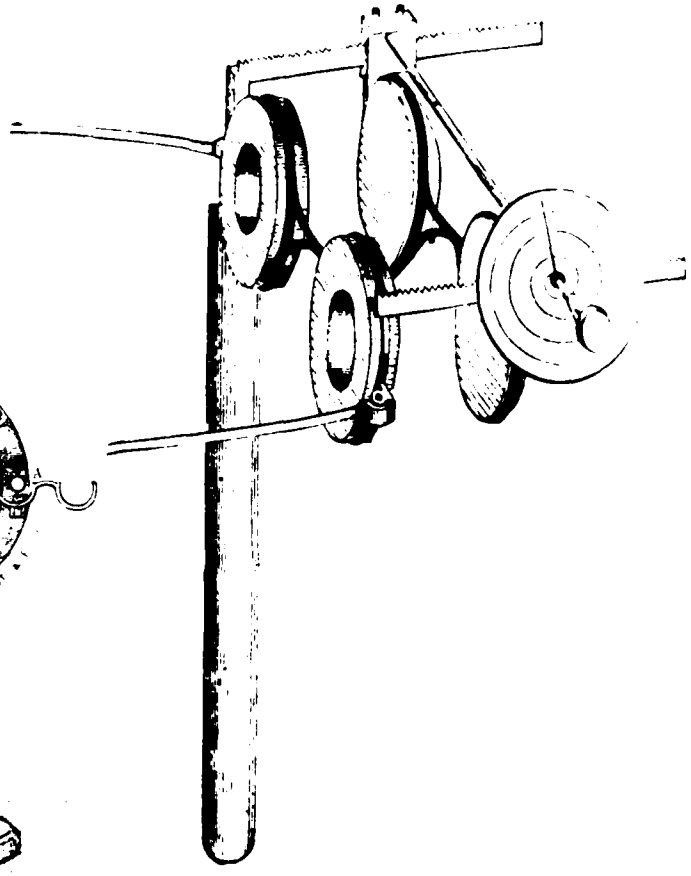


FIG. 3-7b. Snellen's binocular optometer.

frame and lens set by a portable apparatus consisting of a right-eye and left-eye battery of very small spherical lenses coupled together by an adjustable nasal base fitting. The interpupillary distance of the optometer was also adjustable and external cells were provided for the insertion of cylindrical lenses.

Smee (1854) devised an instrument called a visuometer, constructed according to a principle put forward by Hawkins and used for determining the range of accommodation and convergence. It consisted of a graduated optical bench along which test fields could be moved. At the ocular end were four convex lenses of powers 2, 4, 8, and 16 diopters. The test fields were observed through one of these lenses. A full description of Smee's visuometer was given by Donders (1864).

The Galilean Telescope

Galileo's telescope consists of a relatively high-power negative eyepiece and a relatively low-power positive objective lens. By varying the separation of the two lenses the vergence of light leaving the eyepiece may be controlled and used to measure the refractive state of the eye.

Von Graefe (1863) seems to have been first to document the use of the principle of the Galilean telescope as an optometer. Unfortunately, von Graefe used lenses of low power, which produced undesirable differences in the magnification of the retinal image as the vergence changed. Snellen later reduced the magnitude of this problem by using a Galilean system consisting of a –40 diopter eyepiece and a +20 diopter objective. Of course changes in separation of the the lenses were more critical. Snellen recommended that the instrument be used binocularly in the interests of relaxing the patient's accommodation. For this reason Snellen mounted the eyepiece and objective lenses in a double spectacle frame in which the pair of objectives were shifted by means of a twin rack-and-pinion system (Fig. 3-7b).

The Astronomical Telescope

The principle of the astronomical telescope has also been frequently used to form an optometer. The image is inverted but otherwise this system is more efficient than the Galilean telescope, since the exit pupil of the optometer may be made to coincide with the entrance pupil of the eye. The field of view is larger than that of the Galilean telescope and the real images produced by the objective can be accurately located on a suitable graticule and measured directly. The problem of the inverted image is readily solved. As with all telescopes, the vergence of light leaving the eyepiece may be controlled by variations in the separation of the eyepiece and objective.

Hirschberg (1877) devised an optometer based on the principle of the astronomical telescope. The focal length of the objective was 40.5 mm; that of the eyepiece, 27 mm. The lenses were mounted at the ends of two tubes, telescoped by means of a rack and pinion. The instrument was capable of measuring hypermetropia and myopia of 12.33 diopters by changing the separation of the lenses through a distance of 21.5 mm from 60.5 mm to 82 mm. The instrument was calibrated in intervals of 0.5 diopter. Hirschberg drew attention to the fact that, unlike the Galilean telescope, the astronomical telescope could be reversed and still remain an optometer. Only the constants of the instrument have to be changed. Thus, a reading for each position of the instrument provided the practitioner with a means of verifying the result.

One serious disadvantage of any telescopic optometer is the magnitude of the displacement of its components for a reasonably useful measuring capacity. This difficulty was overcome to a large extent in some instruments by the use of a total internal reflection prism. The Ruka Variator designed by Thorner and manufactured by Runge and Kaulfuss is an example of such an instrument in which the objective and eyepiece of the optometer remain stationary while their effective separation is changed by a factor of two by a shift in the position of a total reflection prism along the optical axis of the optometer. The instrument was calibrated on the movement of the prism and is referred to later.

All monocular optometers stimulate active accommodation. This inherent anomaly of the device almost invariably leads to the measurement of excessive amounts of myopia and reduced amounts of hypermetropia. However, it is interesting to know that there has been a recent revival of interest in a telescopic optometer by Guyton, who was awarded a U.S. Patent in 1972.

The Scheiner Experiment

Christoph Scheiner (1619), a contemporary of Newton, is perhaps best remembered for what is still called Scheiner's experiment. The experiment proved that the eye cannot accommodate simultaneously for a distant and near object. The experiment is familiar to most students of elementary physiological optics. If the pupil of the eye is covered by an opaque baffle containing two pinholes separated by a distance that enables them both to be included in the area of the pupil, objects in planes other than the plane of focus will be seen in diplopia, owing to the formation of pairs of relatively small separated blur circles on the retina. Scheiner could not or did not explain his experiment. This task was left to Jacob de la Motte of Danzig (Shastid 1917). However, Scheiner's principle did provide the basis for the development of several varieties of optometers, including the Acuity Systems 6600 Autorefractor. The first of these optometers was attributed to Porterfield (1759). Porterfield's optometer was further developed by Young

(1801). Later Young's optometer was simplified by Lehot (1829). All these instruments consist of a small black board along which is stretched a fine white thread. The board is held horizontally so that the patient's eye is at one end of the white line. The eye views the line through a baffle containing a row of tiny apertures. The baffle is placed very close to the eye. The line is seen singly only at a point which is conjugate with the retina. Elsewhere it is seen as a set of multiple lines diverging forward and backward from this point. The observer will see as many lines as the number of tiny baffle apertures contained in the area of the pupil. Young's main interest in the optometer was to measure accommodation. In the form devised by Young its use was limited to measurement of myopia and the punctum proximum. According to Landolt (1886), its versatility was increased by the addition of a strong convex lens, which he attributes to Stampfer. Stampfer used a tube containing two diaphragms. The one at the eyepiece was equipped with two slits a little over 1 mm apart and each about 0.7 mm wide. The tube was furnished with a convex lens of about 8 diopters. The diaphragm on the other side of the lens contained a single slit of 0.1 mm width, which was covered with ground glass. This slit was parallel to those in the eyepiece. Measurement was made by moving the second diaphragm along the axis of the instrument until the slit appeared single. Thus the artificial far point of the eye is known. The magnitude of the ametropia was easily obtained by subtraction of the effect of the optometer lens. This instrument was suitable for measuring astigmatism and is basically the design currently being employed by some manufacturers in Europe, where more sophisticated versions of these instruments still enjoy some popularity.

Another optometer based upon the Scheiner principle was the prisoptometer of Culbertson (1886). The optical system consisted of a single glass prism, the apex of which divided a small circular aperture in a baffle into a bipartite field. The baffle and prism could be rotated through 360°. The patient viewed a distant white circle through the bipartite field. The monocular diplopia induced by the prismatic eyepiece of the instrument was such that the two circles just touched tangentially in emmetropia, overlapped in myopia, and appeared separate in hypermetropia. Astigmatism was detected by revolving the bipartite prism field. An improved commercial version of the optometer with cells for carrying corrective lenses was patented in 1904 and manufactured by Standard Optical Co. of New York.

Holden's optometer was yet a further example of the extent to which the Scheiner experiment has been used in optometer design. This instrument consisted of an opaque disk containing two perforations, 1 mm in diameter and 4 mm apart. A vertical prism of red glass was placed in front of one of the perforations. The disk was placed before the patient's eye with the perforations occupying a horizontal line in the pupillary area. On viewing a small distant light source, the emmetrope will report that two lights are observed in vertical alignment, whereas the ametrope will report that the red and white lights occupy an oblique meridian.

Landolt (1886) describes another optometer based on the measurement of blur circles. The inventor was Thomson, an American ophthalmologist. The instrument was called an ametrometer (Fig. 3–8). *A* and *B* were small gas flames. *A* was stationary; *B* could be moved along a graduated scale *T* by means of slide *C*. *A* and *B* could be separated by up to 30 cm. By raising or lowering the scale, *B* could be made to rotate around *A* through an angle, the magnitude of which was shown on scale *F*. The gas flames were each about 5 mm in diameter and were observed at a distance of about 5 meters. An emmetrope observed two clear small luminous sources. An ametrope, on the other hand, observed two blur circles, the sizes of which were proportional to the degree of ametropia. This size was measured by movement of the source *B* until the two blur circles just touched tangentially. The distance between *A* and *B* was equal to the diameter of each blur circle. This result was directly related to the ametropia, which could be read off the scale. Based upon an observation of Czermak (1850), Thomson also described a method of determining the nature of the ametropia. A red filter was moved into the field of the pupil, which caused each blur circle to appear as if the red filter was moving across it. In hyperopia the movement seems to be in a direction opposite to that of the filter whereas in myopia it seems to be in the same direction as the filter. This observation is easily explained. In the case of

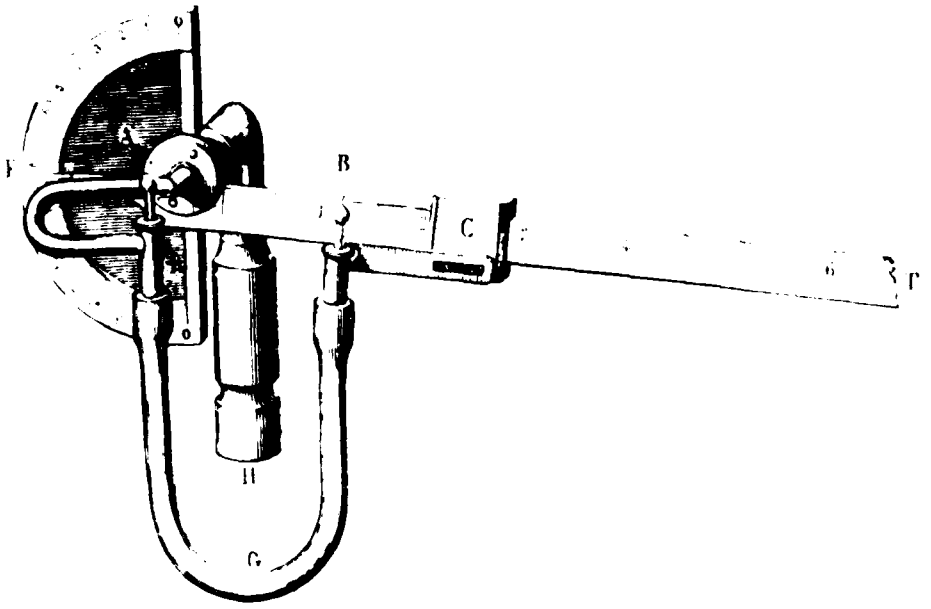


FIG. 3-8 Thomson's ametrometer

hyperopia the colored portion of the refracted cone of rays is intercepted by the retina before it reaches a focus. The reverse occurs in myopia. The inversion of the projected retinal images in each case gives rise to the perceived effect. In astigmatism the diffusion patches appear to be elliptical. In these cases source *B* would be rotated around source *A* so that the two principal meridians as well as the magnitude of the astigmatism could be found.

Mile (1837) demonstrated that if the more distant of two spatially separated objects is viewed monocularly through a single small pinhole in a baffle, any slight movement of the pinhole across the pupil causes the nearer of the two objects to appear to move in the opposite direction. On changing fixation to the nearer object, the more distant one appears to shift in the same direction as the moving pinhole. The principle of this observation has been used to measure ametropia and is related to the movement of the speckled pattern in the gas laser optometer.

The Chromatic Aberration of the Eye

Landolt (1886) described the theory of an optometer composed simply of a disk of cobalt glass. Such a glass transmits a relatively high proportion of red and blue light but absorbs the middle region of the visible spectrum. The basis of measurement depends on the fact that the human eye exhibits a significant amount of chromatic aberration. If a small source of white light is observed through a cobalt glass filter, the power of the eye is less for the transmitted red light than for the transmitted blue light. Thus, in hypermetropia, the combination of blur circles on the retina results in the central portion of the image having a more bluish appearance to the patient, whereas in myopia it should have a more reddish appearance. In the emmetropic eye, the blur circles for the dominant transmission colors are of approximately equal size and produce a magenta image. The most widely used version of this optometer today is the bi-chrome or duo-chrome test for refining the spherical ametropic component.

Objective Optometers

Various objective optometers have been developed for measuring the static refraction of the eye. Among the more notable of these instruments are the Astron Refractometer, the

Rodenstock Refractometer, the Thorner Eye Refractometer, the Zeiss Parallax Refractionometer, and the Fincham Coincidence Optometer. The optical design of these instruments is in almost every respect similar to that of the subjective optometers. The single design feature that differentiates one group from the other is the principle of reversibility of the optical path: rays that follow a specific pathway through an optical system retrace that same pathway if the direction of the light is reversed. The response is thus transferred from the patient, for whom a clear retinal image provides the stimulus, to the practitioner, for whom a clear image of the patient's fundus provides the stimulus.

Among the simplest forms of objective optometer are the direct and indirect ophthalmoscope. In the former case, lenses are interposed between the eye of the patient and the practitioner to compensate for the algebraic sum of manifest refractive errors of both. In the latter instrument a strong convex lens is used to form an inverted real image of the fundus in the space between the patient and the practitioner. This image could be in theory received on an external screen, a procedure that is not practical under ordinary circumstances, since there is usually insufficient light for the purpose. Under special circumstances, such as fundus photography, the intensity of the source may be momentarily increased. In applying the principle of indirect ophthalmoscopy to the optometer, the first requirement is to determine the distance for the convex ophthalmoscope lens at which an inverted image of the fundus is formed. To find its position, Loiseau and Warlomant (1879) used a plane polished glass that occupied only a portion of the tube of the instrument, which they called an ophthalmoscoptometer. They placed the reflector between the lens and the eye under examination in order to avoid the inconvenience of illumination from behind the screen and reflections from the ophthalmoscope lens. However, they were forced to use a transparent mirror, which considerably reduces its reflecting power and thus the illumination of the fundus and the inverted image.

Schmidt-Rimpler (1877) introduced an ingenious idea for measuring the ametropia by focusing the image of an object on the fundus by means of the combined dioptric system of the optometer lens and the eye. The optical system is illustrated in Fig. 3–9. When the convex lens L is placed in front of an eye so that its second principal focus coincides with the anterior principal focus, anterior principal point, or anterior nodal point, the position of an object O, or the image of a source such as S formed at O by the concave mirror M, is always at the same distance from the lens L when it is clearly focused on the retina of the eye with ametropia of similar magnitude. The plane containing O also contains a clear inverted image of the patient's fundus. Thus the source image O, which may be any suitably illuminated target such as a grid at S, and the clear inverted image of the patient's fundus, will be visible to an observer looking through the central aperture C of the mirror M. The point O and the clear image of the fundus shifts from the anterior principal focus of the lens L in a manner directly proportional to the magnitude of the ametropia by an amount expressed in meters per diopter of ametropia, which is equal to the reciprocal of the squared dioptric power of the lens L. The magnitude of this shift is therefore a measure of the ametropia. The two images are formed farther away from the lens

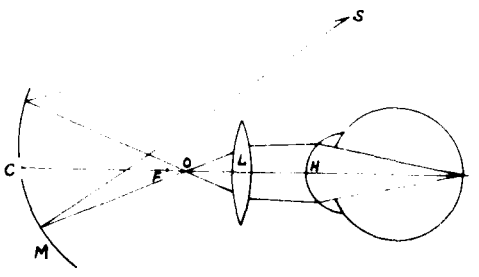


FIG. 3–9. Schmidt-Rimpler principle.

hypermetropia and nearer to it in myopia. The basic optical principles of this system have been used in some ophthalmoscopes and many of the objective optometers.

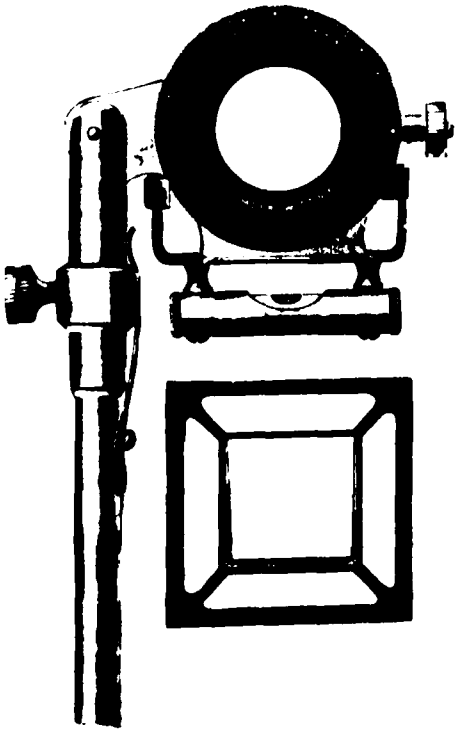
The modern eye refractor seems to have evolved from attempts to produce more sophisticated trial frames. The instruments that are available today did not emerge fully developed from the mind of any single inventor. They are the products of the investigations, devices, experiences, and suggestions of a variety of enthusiastic students of optics, physiology, optometry, and ophthalmology. Fundamentally they are based on the laws of optics as applied to vision care.

Some of the early instruments, called phorometers, were used in conjunction with trial lens sets. They were designed specifically for investigating ocular motility. Following von Graefe's investigation of phorias with a hand-held prism, the first of these new instruments was Stevens's binocular phorometer which appeared in 1888. This instrument is an integral part of many modern eye refractors and is so well known that little need be said about it.

The limitations of the Stevens phorometer were overcome by Wilson. His instrument consisted of two cells fitted with a spirit level for alignment purposes and supported on an adjustable stand. Fixed prisms contained in a suitable holding disk could be rotated into the aperture of the right cell. This system has almost completely replaced the Stevens phorometer in modern eye refractors. It has the advantage that both phorias and ductions may be measured with the one system.

Savage first recognized the desirability of testing ocular motility with a monocular instrument and devised a suitable instrument for the purpose. It consists of a reversible 10-diopter Risley prism mounted in a holder equipped with a spirit level (Fig. 3-10).

The discovery of the fundamental functional activity of the oblique muscles is attributed to Savage (Price 1918). In 1893 Price first advocated the adoption of the term *cyclophoria* to describe the rotational phorias. The first of the instruments used to test cyclophoria was devised by Price (1893) and demonstrated in 1894. Price's phorometer was a simple device used in a regular frame (Fig. 3-11). The right cell was fitted with a Maddox biprism combined with a Maddox rod with its axis parallel to the base-apex line of the biprism. The left cell was fitted with a standard Maddox rod with its axis running in the same direction. When a small light source was fixated by the patient, any departure from parallelism of the central line from the remaining two lines indicated the presence of cyclophoria. Savage later redesigned the instrument for measuring both cyclophorias and cycloductions. He called this instrument a cyclophorometer.



Another entirely portable monocular phorometer was the Wells handy phorometer (Fig. 3-12), which was a small hand-held instrument. It consisted of a 10-diopter prism mounted in a frame having attached to it a weighted pointer by which the effective horizontal or vertical component of the instrument prism was indicated for its current position. Although the instrument was monocular, the optical principle involved was similar to that of the Stevens phorometer, the single prism in this case serving as both the displacement and measuring prism.

FIG. 3-10. Savage's monocular phorometer.

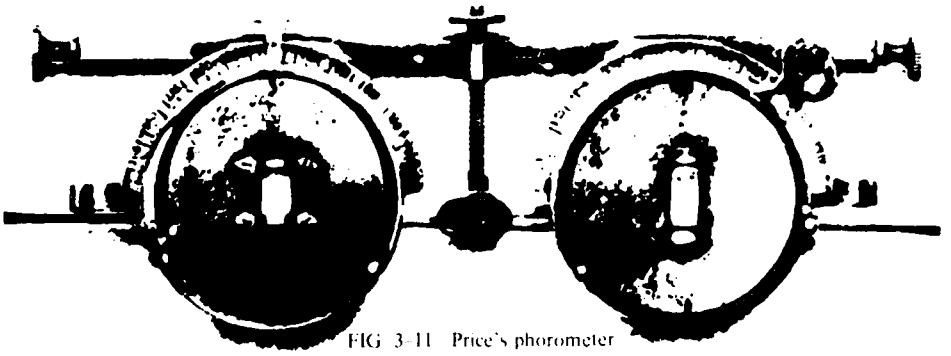


FIG. 3-11 Price's phorometer

Eye Refractors

The modern eye refractor began to emerge in the early years of the 20th century, largely owing to the work of De Zeng. His first patent (for a telescopic optometer) was awarded in 1895. De Zeng was granted a number of additional patents between 1908 and 1922 for inventions that ultimately became incorporated into the three instruments by which his name has been perpetuated. The first was the De Zeng phorometer-trial frame (Fig. 3-3), a trial-case-assisted phorometer that included a hinged Stevens phorometer, a Risley prism, and multiple Maddox rod with twin cells for trial lenses. The interpupillary distance was adjustable and a spirit level was provided for alignment. The second was the De Zeng Phoro-Optometer (Fig. 3-13). This was a much more sophisticated unit, which included all the features of its predecessor but was now fitted with a pair of 30-diopter Risley prisms and two multiple Maddox rods. The trial-lens cells were equipped with axis scales for holding cylindrical lenses; spherical lens power was provided as an integral part of the instrument. Each of the spherical units consisted of one disk of low-power lenses and one disk of high-power lenses arranged on a common spindle so that combinations of one lens from each disk could be placed in tandem in front of the patient's eye.

American Optical Co. became interested in the De Zeng Phoro-Optometer and in 1928 released an instrument incorporating some further modifications and improvements, the Improved Wellsworth De Zeng Phoropter, Model 588. It was very similar to the original Phoro-Optometer and provided a range of spherical lens combinations from -8.00 to +7.75 diopters in intervals of 0.25 diopter by means of two concentric disks of low- and high-power sphericals. This interval could be reduced to 0.12 diopter by the use of an auxiliary lens. Right-

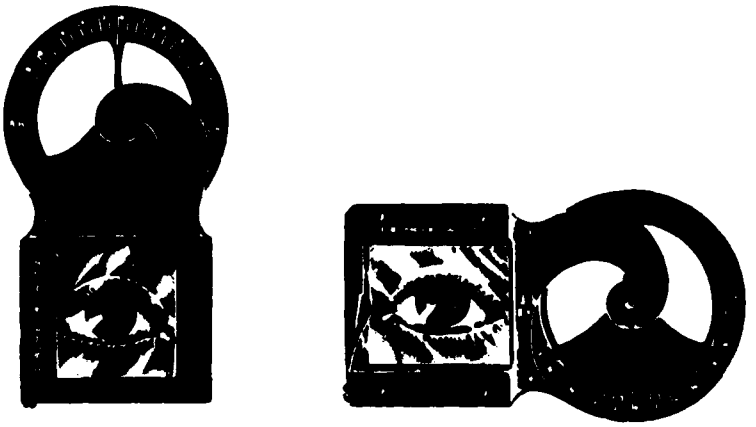


FIG. 3-12 The Wells Handy phorometer.

[illegible] eye cylindrical units were added to the instrument. Each consisted of two concentric [illegible] of minus cylindrical lenses that could be pivoted on the sight hole of the instrument for [illegible] control. Combinations of minus cylindrical power from 0.00 to −1.25 diopters in intervals of [illegible] diopter and to −4.75 diopters in intervals of 0.25 diopter could be provided. The Stevens [illegible] meter was superseded by three displacement prisms of powers 6 diopters base up, 10 [illegible] degrees base in, and 15 diopters base out, which were contained in a disk of auxiliary lenses. [illegible] two Risley prisms, the two multiple Maddox rods, and the spirit level were retained from [illegible] previous design. The compact nature of this instrument was a feature of the De Zeng [illegible] gn. He claimed that this sort of instrument should be small, neat, and sanitary, covering a [illegible] mum portion of the patient's face. Earlier disk optometers had been rather cumbersome de- [illegible]. All the above De Zeng instruments had been supported from below. American Optical Co. [illegible] ced this instrument with a more versatile eye refractor, which was suspended from above.

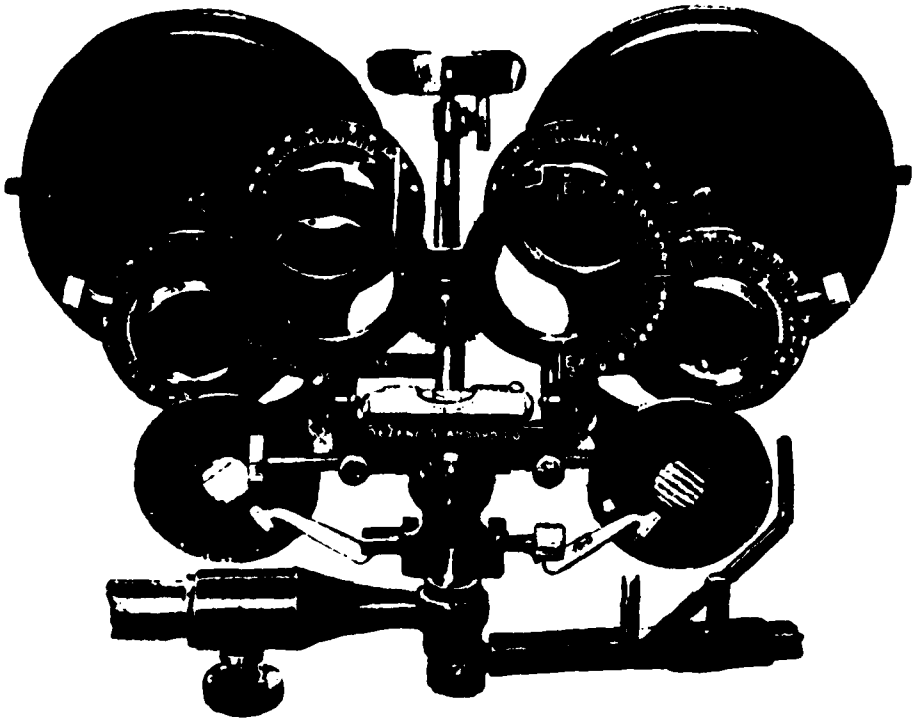


FIG. 3.13. The Phoro-optometer, De Zeng.

This was Model 589, in which the spherical range was extended from −19.00 to +16.75 diopters in intervals of 0.25 diopter and the cylindrical range from 0.00 to −6.00 diopters in similar intervals. This arrangement of spherical and cylindrical lenses has been perpetuated in all subsequent American Optical Co. eye refractors to the present day. An operational weakness of Models 588 and 589 was evident during the examination of astigmatic patients with relatively small interpupillary distances, for whom interlocking of the milled edges of the two cylindrical lens units could occur at some axis positions. In 1948 Model 590 was introduced. This model included some major improvements over the earlier instruments, although the normal range of the instrument was similar to that of Model 589. However, cylindrical lenses were relocated within the main housing of the instrument and a pair of −2.00-diopter plug-in cylindrical lenses were provided as accessories, which extended the cylindrical range to −8.00 diopters. Cylindrical power

and axis changes were effected for the first time by means of a pair of concentric knobs. It is the writer's opinion that this instrument was the most advanced of its day and probably represented an optimal compromise between simplicity, quality craftsmanship, and clinical excellence that has never been surpassed in a manually operated eye refractor. In many ways it is a pity that production of this model was discontinued in favor of the glossier, gadget-endowed Rx Master and Ultramatic eye refractors marketed by the same company. Both of these instruments have a similar lens inventory to the Additive Phoropter Model 590. The notable differences are in the complement of auxiliaries.

In 1926 two patents were awarded to Hans Clement and Bernard Parron for an eye refractor by which various combinations of spherical and cylindrical lenses could be obtained by the rotation of knobs or the movement of levers. The patents were assigned to the General Optical Co. of New York; the Genothalmic Refractor was the result. Its lens inventory was contained in six disks, which were enclosed within a lacquered white metal housing. The front disk included three plano-concave spherical lenses with the plane surfaces leading, a fixed cross cylinder for near testing, and an occluder. The second and third disks contained low- and high-power plano-convex spherical lenses, respectively, with the curved surfaces leading. These two disks provided positive lens power ranging from 0.00 to +8.75 diopters in intervals of 0.25 diopter. Disk 4 contained three relatively high-power plano-cylindrical lenses; Disk 5, three relatively low-power plano-cylindrical lenses. The leading surfaces of all the cylindrical lenses were curved. Negative cylindrical power ranging from 0.00 to –3.75 diopters in intervals of 0.25 diopter was thus provided. The axes of all the cylindrical lenses in each pair of disks could be changed simultaneously by means of a spring-loaded lever, which operated a planetary system of gears. The final disk contained three high-power auxiliary plano-spherical lenses. They were +9.00, -9.00, and –18.00 diopters and extended the nominal spherical range of the instrument from -18.00 to +17.75 diopters. These lenses were brought into position in the sight hole of the instrument by means of a short lever. The leading surfaces were the curved surface of the positive lens and the plane surfaces of the negative lenses. Some attempt seems to have been made to compensate for changes in lens effectivity brought about by their different distances in front of the patient's eye. The sight hole was 36 mm long with an aperture of 21 mm. The internal lens stack was about 25 mm thick. The patent specifications emphasize the mechanical apparatus by which the lenses are transported into the prescribed position in front of the patient's eyes. No claims were made concerning the design of the component lenses.

Hartinger (1931) described a new eye refractor designed by Henker and produced by Carl Zeiss of Jena. Although it was a more compact binocular instrument, both its mechanical and optical arrangement was very characteristic of one of the Javal optometers. It consisted of three disks of lenses, two spherical and one cylindrical. All the cylindrical lenses were fitted to geared rings and could be rotated to any prescribed axis by means of a master planetary gear. All lenses were Zeiss Punktal spectacle lenses of 12 mm aperture. The nominal range of the instrument extended from +23.50 to –31.50 diopters of spherical power and from +6.00 to –6.00 diopters of cylindrical power. The cylindrical range could be extended to ±10.00 diopters with the aid of a pair of ±4.00-diopter auxiliary cylinders. With the refractor was supplied an extensive box of accessories including prisms, Maddox rods, Maddox biprisms, tinted lenses etc., and a box of telescopic and microscopic lenses for the treatment of the partially sighted.

Three U.S. patents were filed between 1926 and 1932 by Hunsicker for an eye refracting instrument. Two were awarded in 1931 and a third in 1934. Two of these patents were assigned to Aaron S. Green and Louis D. Green of San Francisco. Interest in these patents by Bausch and Lomb resulted in the manufacture of the Greens' Refractor, undoubtedly the most widely used manual eye refractor of the 20th century. The main instrument included four disks of lenses. The first was a battery of negative plano-cylinders with the cylindrical surfaces leading. The powers varied in intervals of 0.25 diopters. This disk was followed by a disk of low-power positive plano-sphericals with the plane surfaces leading. These lenses were also ordered in intervals of 0.25 diopter to +3.75 diopters. In the instrument examined by the writer, the +2.25 sphere had been fitted back to front. The third disk of high-power plano-spherical lenses,

with their plane surfaces leading, included a range of lenses from +16.00 to −28.00 diopters in steps of 4.00 diopters. The final disk of auxiliary lenses contained a pinhole, an occluder, an open aperture, a +0.12-diopter spherical, and a +2.00-diopter sphere for retinoscopy. A box of plug-in auxiliary lenses included a pair of −0.12, −2.50, and −5.00 diopter plano-cylindrical lenses with the plane surface leading. The nominal range of the instrument is therefore from +19.75 to −28.00 diopters of spherical power in intervals of 0.12 diopter, from 0.00 to −2.75 diopters of cylindrical power also in intervals of 0.12 diopter, and from −2.75 to −7.50 diopters of cylindrical power in intervals of 0.25 diopter. If the final auxiliary disk and the plug-in lenses are excluded, the thickness of the three-lens sphero-cylindrical stack is approximately 9.56 mm. The length of the sight hole is 29 mm and the aperture of the instrument is 16.8 mm maximum. It is surprising that Bausch and Lomb did not incorporate the Kellner principle for which they had been assigned the patent in 1918. The instrument is not equipped with a corneal vertex distance measuring system. This simple addition would certainly have improved its versatility in dealing more adequately with prescriptions of medium and high power. As it is, the extreme range of the instrument is rarely used and seldom trusted. Bausch and Lomb have released a more trendy version of the instrument which some may find of more pleasant appearance. It is referred to as the Greens' II. There are no major changes to the optical system. The Jackson cross cylinders are rotated and flipped by means of a pair of concentric knobs, which are synchronized with the cylinder axis control. The external adjustable Maddox rods and Risley prisms are retained.

From the United Kingdom, two eye refractors bearing a marked similarity to the Genothalmic Refractor have emerged from the Ellis Optical Co. of Croydon. The first was called the Examinor. The second, the British Refracting Unit, must surely be hailed as the dreadnaught class amongst eye refractors. It contained no fewer than 8 independent disks of lenses. It was an extension in design of the Examinor. The first disk included a similar set of auxiliaries. Disks 2 and 3 contained the low- and high-power positive plano-spherical with convex surfaces leading. These disks were followed by disks 4 and 5, the high-and low-power negative plano-cylinders with plane surfaces leading. Disks 6 and 7 contained the high-and low-power negative plano-spherical with the plane surfaces leading. The final disk was a battery of auxiliary ±9.00 diopter spherical. With such an array any attempt to control effectivity would be worthless. The aperture of the instrument was 20.5 mm and the length of the sight hole, 43 mm. The thickness of the lens stack reached a record magnitude of 30 mm. Two front cells on each side of the instrument were provided for additional lenses.

An eye refractor of continuously variable power was described by Retina (1937). The instrument was designed by Thorner and manufactured by Runge and Kaulfuss. It became known as the Ruka Variator and incorporated a Stokes-Javal lens consisting of a positive and a negative 3.00-diopter cylindrical lens mounted coaxially in a geared unit to rotate in opposite directions. As the lenses were rotated from the axes-parallel position to the axes-crossed position a cylindrical component was generated which changed in magnitude from 0.00 to 6.00 diopters. Since the two cylinders rotate in opposite directions by equal amounts, the axis of the resultant cylinder remains constant at an angle of 45° to the axes parallel meridian. However, the lens also produces an undesirable spherical component of half the power of the resultant cylinder but opposite sign, which must be neutralized. This goal was achieved by means of a unit magnification astronomical telescopic optometer, the optical path of which could be varied and reversed with a total internal reflection prism. This optometer also provided continuously variable spherical power ranging from +20.00 to −20.00 diopters. The instrument was heavy and cumbersome and the aperture was very small. More than half of the incident light was lost by reflection at the surfaces of the various optical elements. Nevertheless, the Ruka Variator has some very useful features.

Modern eye refractors following the American pattern are of relatively recent origin in Europe. Two of the more notable instruments in this group are the Möller Visutest-C and the Rodenstock Phorovist.

The Visutest-C is a broad-looking instrument, the elements of which are housed in a plastic casing. The sight hole of the instrument is 28 mm long. The aperture is stepped down from 25 mm at the front to 19 mm at the back. Access to the internal lens disks from the patient's

side is prevented by means of a cover glass, which is screwed into the rear aperture of the housing. A corneal vertex distance indexation marker is provided, which allows the practitioner to locate the corneal vertex 12 mm behind the back vertex of the cover glass. No complementary scale is provided for the practitioner's use of some other vertex distance. There is provision for lever-controlled convergence of the two optical axes of the instrument for near testing. However, unlike the instruments with that feature which have been produced by American Optical Co., the change in interpupillary distance is not automatically registered on the appropriate scale. The forehead rest has 23 mm of adjustment. The right half of the instrument may be raised or lowered by 5 mm with respect to the left half to compensate for facial asymmetry. A novel double-cross cylinder unit designed by Reiner replaces the standard Jackson type. This is the Astimess cross cylinder, which consists of two crossed cylinders ground on +6.00 diopter base toric form and secured into a geared unit in such a way that both may be revolved simultaneously by a single action, so that common axes always remain at right angles. The double lens unit is hinged so that each lens may be shifted into position in front of the sight hole for comparison purposes. The lenses are interchangeable although ±0.25 crossed cylinders are normally supplied. The main lens inventory is contained in four disks. The front disk contains negative cylinders ranging from 0.25 to 2.25 diopters in intervals of 0.25 diopter. All are of toric form with a back surface power of –6.00 diopters spherical. The second disk contains a set of low-power positive and negative spherical lenses ranging from +1.75 to –1.00 diopter in intervals of 0.25 diopter. The positive lenses are ground on –6.00-diopter base and the negative lenses are ground on +6.00-diopter base. The third disk contains high-power positive and negative lenses ranging from +15.00 to –18.00 diopters in steps of 3.00 diopters. The higher-power lenses are of plano form with the curved surface leading the positives and the plane surface leading the negatives. The lower-power lenses are ground on either –6.00- or +6.00-diopter base curves according to whether they are positive or negative lenses. Four pairs of plug-in accessory lenses are provided. They include plano sphericals; –2.00- and –4.00-diopter cylindricals of meniscus and toric form, respectively, each with a back surface power of –6.00 diopters spherical; and –6.00-diopter toric cylindricals with a back surface power of –12.00 diopters spherical. The nominal range of the instrument is from +26.75 to –29.00 diopters spherical in intervals of 0.25 diopter and from –0.25 to –8.25 diopter cylindrical in similar intervals if the ±10.00-diopter sphericals contained in the auxiliary lens disk and the plug-in cylindrical accessories are used in conjunction with the three main lens batteries. The total thickness of a combination of lenses from each of the five sources is 18 mm. Some attempt is made to control the effectivity of the lens stack in the spectacle plane. Nevertheless, the logic of such control is difficult to follow. Differences between the actual back vertex power and the labelled power of the lenses are confined to the plug-in negative cylindrical lenses, the high-power sphericals, and the plus and minus 10.00-diopter sphericals contained in the auxiliary disk. Compensation is made according to the general rule that lenses increase in effective positive power as they are shifted away from the eye. However, the high-power sphericals are compensated for a plane which lies 6 to 9 mm on the side nearest the eye, whereas the ±10.00-diopter auxiliary sphericals, which are located 1.8 mm closer to the eye, are compensated for a plane about 18 mm closer to the eye. On the other hand, the three plug-in cylinders are compensated for planes 45, 23, and 18 mm, respectively, closer to the eye. In spite of this feature, the instrument is provided with a corneal vertex distance alignment system which is calibrated for 12 mm (according to the manufacturer's specifications). A novel mechanical feature of the instrument is that the presbyopic addition may be indicated independently of the distance spherical correction.

In the mid-1960s the Rodenstock Optical Works of Munich re-entered the eye refractor arena after a lapse of almost 40 years, following an unsuccessful adventure with the Disk Refractometer. The current model is called the Phorovist. The main unit contains four disks of lenses. The front disk contains a series of negative cylindrical lenses ranging in power from –0.25 to –2.75 diopters in steps of 0.25 diopter. These lenses are ground on +6.00 diopter base toric form and mounted into geared rings which engage a planetary gear by which they may be brought into posi-

...e in front of the eye at any prescribed axis. The second disk contains a series of low-power sphericals, the nominal powers of which range from +0.75 to -2.00 diopters in intervals of 0.25 diopter. All these lenses are plano-spherical with the plane surface of the negative lenses and the curved surface of the positive leading. The third disk contains the high-power sphericals in intervals of 3.00 diopters. The nominal powers of these lenses range from -18.00 to +15.00 diopters. The base curves of this series varies throughout the range. The negatives from -3.00 to -9.00 diopters are ground on +3.00-diopter base, which is the leading surface. The same range of positive sphericals is ground on -3.00-diopter base, which is the back surface. Lenses of power equal to or greater than 12.00 diopters are of plano form with the plane surfaces of the negative and the curved surfaces of the positive lenses leading. In the disk of cylinders an open aperture is provided, but the 0.00-diopter aperture of each of the two spherical disks contains a +6.00-diopter base plano meniscus lens. Theoretically the American Optical Co. instruments based on Tillyer principle should have used such a lens, but did not. In the case of the Phorovist such lenses are of dubious value. Even their base curves are not consistent with those of the other lenses in the series. (In the instrument I examined there was no evidence to suggest that any attempt was made to compensate the powers of the lenses for their planes of occupancy. However, some of the lenses were up to 0.25 diopters off true power.) The fourth disk contains a set of auxiliary lenses. Both the front and back ends of the sight hole aperture have been sealed by a plane glass window 1 mm thick. The distance between the two windows is about 24 mm. The thickness of the stack of four internal lenses is 14.5 mm. The back vertex of this stack is 7 mm in front of the back window of the instrument. The external accessories include a pair of 20-diopter Risley prisms and a pair of interchangeable Jackson cross cylinders. Three auxiliary negative cylindrical lenses of powers 2.00, 4.00, and 6.00 diopters, respectively, are provided. These lenses plug into the front end of the sight hole, where they are engaged by the regular axis-setting control. The back vertex of these lenses is 18.5 mm in front of that of the internal lens stack. However, the plug-in cylinders are power compensated for planes 28, 21, and 17 mm, respectively, behind their back vertices. The corneal vertex distance alignment system is calibrated for a back vertex distance of 18 mm. The total length of the sight hole is 31 mm, its aperture is 18 mm, and all lenses are vacuum coated against reflections. A useful feature of the instrument, at least in principle, is a warning light that indicates when the patient has moved off the forehead rest. Electrical contact failure in the switch has given the writer sufficient concern to regard any further time spent in servicing this part of the instrument as a waste of effort.*

A number of eye refractors of Japanese origin have appeared recently. Some of the earlier models were rather inferior reproductions of American instruments. They have included the MOS Phoropter and the TOC T-10, both of which closely resemble in appearance the Greens' Refractor, and the New Cherry Precis-o-matic Phoropter, which bears a strong external similarity to the American Optical Ultramatic Phoropter.

Within the past decade Topcon Optical Co., after producing one or two less ambitious instruments (Models VT-J and VT-D), finally released the Vision Tester model VT-SD. This model must surely be the most well-presented eye refractor package thus far produced. One cannot help but be impressed by its external appearance. Only the more adventurous will have lifted its gleaming covers to peer at the optical system that lies beneath. I have had the disappointment of studying two VT-SD eye refractors in this way. Both were brand new instruments; a period of about one year elapsed between my examination of the first and second instrument.

The VT-SD features one or two innovations. The principal innovations are the 0.50 cross cylinder loupe (Auto Cross) and the duochrome loupe. The physical arrangement and optical presentation of both loupes is similar. Each is essentially an opaque carrier disk containing two symmetrical apertures of 14 mm diameter on 16 mm centers. Each aperture is fitted with a 3-diopter displacement prism with its base toward the center of the carrier disk. The Auto Cross

*The manufacturer of the Phorovist claims to have eliminated much of the criticisms referred to in the above evaluation of the instrument.

is also fitted with two crossed cylinders with similar axes at right angles to one another. A rim lever enables the carrier disk to be rotated through an angle of 45° for checking the power or the axis of the corrective cylinder. The unit may be automatically coupled to the normal axis control provided that no additional plug-in accessory lenses are required. The advantage of the device is that the Maddox biprism produces monocular diplopia of the test target for simultaneous comparison of the first and second cross cylinder images by the patient. The duochrome loupe functions in a similar way, the diplopia images in this case being observed respectively through a red or green filter. The third loupe is a fully adjustable 15-diopter Risley prism. One Risley prism was out of adjustment by 8 prism diopters in the first instrument I examined. A set of these three accessories is, of course, provided on both sides of the instrument. The alignment is carried out with the aid of a disk spirit level which is normally covered by a hinged polished metal plate that also serves as a visual access mirror when raised to the 45° position.

The internal lens stack is protected by front and rear flat glass cover plates that screw into the sight hole. The center thickness of each cover glass is 1.6 mm and the aperture is 18.5 mm. The sight hole length is a record 48 mm with the Auto Cross coupling plug in position and 45 mm with it removed. There are five internal disks of lenses. The first is a battery of low-power negative plano cylinders with the cylindrical surface leading. The second disk contains high-power negative plano cylinders with the plane surface leading. The two disks are mechanically linked so that for every full rotation of the first disk the next high-power cylinder is automatically shifted into position in the sight hole. This is standard procedure in most modern instruments. In less than a year's usage, the cylinder unit of one instrument has developed a mechanical failure. The two lens disks referred to above rotate on a steel spindle in a nylon bearing. The coupling of the two disks is effected by means of a system of gears. The nylon bearing has caused the steel spindle to wear and the coupling gears sometimes slip out of mesh. This fault has produced both axis and power errors to be recorded and has created a general feeling of uncertainty and unreliability with respect to the instrument. The nylon bearing has been replaced with bronze. The -3.75- and -5.00-diopter cylinders in disk two have an actual back vertex power of -3.90 and -5.37 diopters, respectively, presumably in an attempt to compensate for the forward position of the cylinder unit. The nominal and back vertex powers of the spherical lenses are equal. The third disk is a battery of low-power spherical lenses ranging from -1.00 to +1.75 diopters in intervals of 0.25 diopter. The lenses are of plano-concave and plano-convex form. In both of the instruments examined several of these lenses appeared to have been fitted into the disk back to front. They are asymmetrically vee bevelled and held in position by means of a circular wire clip. Because of the asymmetry of the bevel it is difficult to set the lenses correctly short of cementing them into position. Disk number four is a battery of high-power sphericals ground on +3.00-diopter base meniscus form. They range in power from -18.00 to +15.00 diopters in steps of 3.00 diopters. Power modifications have been used in an attempt to compensate for a forward position of this battery of lenses by a distance of about 3 mm. That is, apparently for the plane of disk 5, the disk of internal auxiliary lenses. These lenses include an open aperture, an occluder, a fixed crossed cylinder, a polarizing lens, a vertical and horizontal multiple Maddox rod, 15 diopters base out, 10 diopters base in, and 6 diopters vertical dissociation prisms, a pinhole, and two spherical lenses for retinoscopy of powers +2.00 and +1.50 diopters, respectively. The total thickness of a stack of lenses comprising one from each of the five internal disks is 23 mm. The distance between the auxiliary lenses and the back cover glass is 6.8 mm.

The instrument is provided with a corneal vertex distance alignment system calibrated for 12 mm. A millimeter scale is clearly visible on both sides of the zero position. When the patient is aligned on the zero marker, the corneal vertex is located 7.5 mm from the rear cover glass. This is not practical and zero alignment will be unattainable in most cases if 2 mm is allowed for the thickness of the eyelids and 7.5 mm for the upper eyelashes. A small red marker appears in a window at the front of the instrument when the patient is in contact with the forehead rest. This

...ker is not easily visible at levels of illumination customarily employed in practice.

A box of plug-in auxiliaries is also provided and contains pairs of lenses of the following ... powers (the actual back vertex power in each case is shown in parenthesis): -2.00 ... cylindrical (-2.62), +10.00 diopters spherical (+7.25), and -10 diopters spherical (-7.50). The effective labelled powers are thus generated in a plane about 38 mm on the eye ... of the 10.00-diopter lenses. However, one finds that when the +10.00-diopter lens is ...gged into position, a spherical power of -8.75 diopters is required in the internal spherical unit ...*beam neutralization*. In the case of the -10.00-diopter lens, neutralization is obtained when ...2.75 diopters of spherical power is provided by the internal unit. All lenses are vacuum coated ...inst surface reflections. For testing at near (35 cm) and intermediate distances (67 cm) the ... curves of the instrument may be converged automatically by means of a coupling which is ...ed when the reading rod is lowered into position.

Modern manual eye refractors at best seem to be a compromise between accuracy and ... convenience. The present investigation of the optical systems employed in eye refractors ...s that a wide variety of different arrangements of lens power, type, form, and position have ...s been used in an attempt to produce a better instrument. Perhaps in despair some ... refractors have *even tried locating some of their lenses back to front*. Are there some basic ... principles on which designers could base a perfect solution to eye refractor design? ...s question is discussed by Lang and Marg (1975). Most users are obliged to rely on the ...ge's of the manufacturer when contemplating the purchase of an eye refractor. Few users ...ther the facilities, the opportunity, or the inclination to make a thorough evaluation of the ...ment they wish to acquire. Perhaps this report will prompt some manufacturers of ...ic instruments to re-examine their standards of quality control and provide the precision ...ments that users believe they are obtaining.

The Risley Prism

...e variable Risley prism has appeared as an accessory on almost every eye refractor yet ... is invariably attached to the front of the instrument housing by means of a hinged ... permits it to be moved into position in front of the sight hole. It can be rotated in ...ge's a scale in such a way that the base-apex line of the resultant prism may be ...ed meridian. The vertical and horizontal positions are located quite positively by a ...ded ball bearing or similar device which engages a suitable depression in the ...

...arefully examined a group of nine different well-known eye refractors, all of which ... Risley prisms. *After an allowance of either* 26 mm or the manufacturer's ...ments had been made for the distance between the back vertex of the lens stack ... rotation of the eye, the back vertex of the Risley unit was located at an aver- ... mm in front of the center of rotation of the eye. This distance was largest ... case of the Topcon Vision Tester Model VT-SD, and smallest for the Greens' ... Möller Visutest-C, in which corresponding distances of 59 mm were measured. ...ugh the forward position of the Risley prism does not affect measurements of ocular ... fixation vision, the instrument readings for similar measurements made at relatively ... vary with the magnitude of the actual ocular rotations which take place. ... due to a reduction in the effective power of the prism, which is a function of its ... from the center of rotation of the eye and the near test field.

Suppose an eye with its center of rotation at R is viewing a near object O which lies on the ... visual axis RO. If a prism of power P prism diopters is placed in front of the eye at a ... from its center of rotation and at a distance l from the object, the eye must rotate ... angle θ to fixate the image O of the original object, formed by the prism. Reference ... 3.14 clearly indicates that for a prism of any power, the magnitude of the angle θ ...gh which the eye must rotate to regain fixation of the displaced image will be reduced as ... increases or l decreases. The angle θ may be expressed in prism diopters and defined as

the effective power of the prism. Using the New Cartesian sign convention with the plane of the thin prism at the origin of a two dimensional coordinate system we have

$$\tan \theta = \Delta\Delta'/(s - \ell) = -(\ell \tan P)/(s - \ell) = (\tan P)/[1 - (s/\ell)]$$

and the effective power of prism is given by

$$\theta^{\Delta} = P^{\Delta}/[1 - (s/\ell)]$$

If ℓ is very large, as is the case when ocular motility is tested for distance vision, the position of the Risley prism in front of the eye makes very little difference to the result and $\theta^{\Delta} = P^{\Delta}$ for all practical purposes. However, if the above formula is used to compute the effective power of the Risley prism when used for measurements of ocular motility at distances of 333 mm and 400 mm, respectively, in front of the back vertex of the lens stack in the eye refractor, significant differences will exist between the scale reading and the actual eye rotation. If an average value of 71 mm is adopted for the magnitude of s, the Risley prism will read too high. The error will be approximately 20% for a near testing distance of 400 mm and 25% for one of 333 mm. In the case of the Topcon Vision Tester (Model VT-SD) the error is 30% at 400 mm and 37% at 333 mm. The errors in the Greens' Refractor and Visutest-C are 16% at 400 mm and 20% at 333 mm.

The American Optical Co. Ultramatic Phoropter and the Topcon Vision Tester (Model VT-SD) are each equipped with three auxiliary prisms of powers 15 diopters base out, 10 diopters base in, and 6 diopters base vertical, respectively. These prisms are located in planes 46.5 mm and 71.2 mm, respectively, behind those occupied by the Risley prism. Therefore, combinations of the Risley unit and the auxiliary fixed prisms cannot be regarded as equivalent to the algebraic sum of their nominal powers when used for near vision tests.

In eye refractors that include a Stevens phorometer, the situation is somewhat worse, since this device is invariably located in front of the Risley prisms.

It is not surprising, therefore, that several clinical studies involving near phoria measurements (Lederer and Pearson 1945) have shown that results obtained with direct-reading nonprismatic instruments, such as the Maddox Wing, which measure the angle of ocular rotation, are almost invariably lower than those obtained with techniques that involve the use of prisms placed some distance in front of the eyes of the same patients.

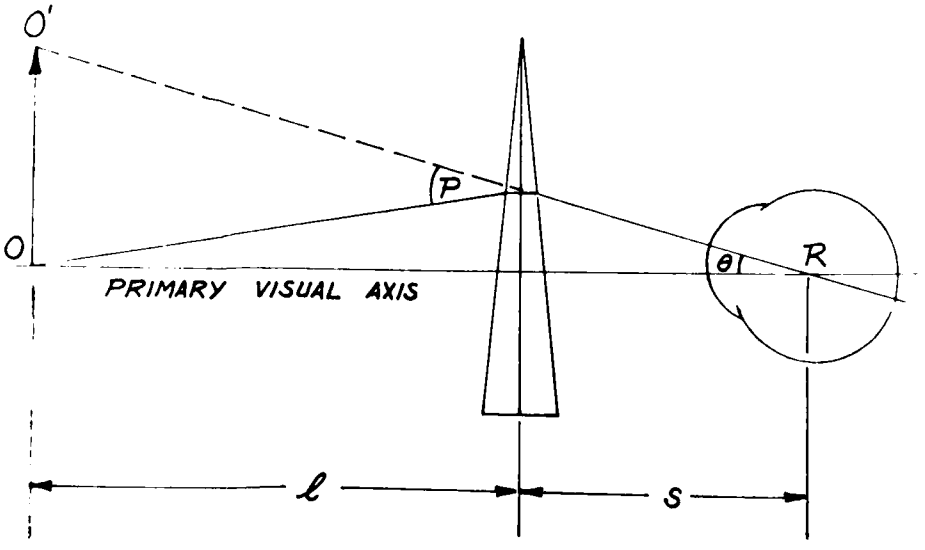


FIG. 3-14. The effective power of a prism.

Automated Instrumentation for the Examination of the Eye

Recent developments in electronics, electromechanics, and electro-optics, and the availability of small inexpensive computers have resulted in the development of new concepts in instrumentation for the examination of the eye. The new instruments being offered to the eye-care professions include a collection of automatic objective optometers, perimeters, eye-movement recorders, case-history evaluation and recording systems, and at least two eye refractors.

The conventional technique for measuring refractive errors is to estimate their magnitude by means of retinoscopy, which is followed by subjective refraction. The latter method is still by far the most accurate technique available. However, alternative methods of clinical refraction are being made available to optometrists and ophthalmologsts in the form of fully automated objective optometers. The 'Ophthalmetron' produced by Bausch and Lomb was the first of these new generation instruments to reach the profession in 1972. It is based upon the principle of retinoscopy. In three seconds a scanning of all meridians of the eye takes place by means of near-infrared radiation and a recording system produces a sinusoidal graph of the refractive state of the eye to the nearest quarter of a diopter. The record for the right eye is printed on one side of a form; that for the left eye appears on the reverse side. The measurement begins and ends at the 80° meridian. The refractive error in sphero-cylindrical form can be evaluated directly from the printout (Safir, Knoll, and Mohrman 1970; Safir, Hyams, Philpot, and Jagerman 1979; Knoll, Mohrman, and Maier 1970; Hyams, Safir, and Philpot 1970 and 1971; Knoll and Mohrman 1971). This instrument is no longer in production.

Another instrument in this category is the 'Dioptron' manufactured by Coherent Radiation of Palo Alto, Calif. This instrument was based on an idea for an automatic optometer by Bellows and Borough of Illinois. Their patent claim was filed in 1968 and accepted in 1970. Bellows, an Illinois ophthalmologist, subsequently sought engineering assistance from the Itek Corp. but was turned down because of the estimated magnitude of the development costs. Development was eventually undertaken by a relatively small engineering firm, Tropel Inc., of Fairport, N.Y. The 'Dioptron' has finally emerged as a product of Coherent Radiation, whose main interest is laser technology. It is a small table instrument whose optical system bears little resemblance to the original concepts of Bello· s and Borough. Alignment of the instrument is effected with a simple joystick control system and a vertical adjustment screw. The light source for the alignment system is operated by one of two pushbuttons. The alignment target is displayed on a screen above the body of the instrument. The remaining button initiates the mechanism that refracts the patient. The standard target in the Dioptron is a Snellen chart, which is viewed binocularly through an adjustable fogging system to assist in relaxing accommodation. The refraction is automatically interrupted for 0.15 second during blinks. Cycloplegics are not required. The instrument may be operated with pupils as small as 2 mm in diameter, and its measuring range is from -10 to +15 diopters. The manufacturers claim the instrument is accurate to 0.25 diopter on power and 5° on axis for cylinders greater than 0.50 diopter and 10° for cylinders of lower power. The optical system is based on the principle of the lensometer. An image is projected onto the retina by means of a movable lens. A second system views the sharpness of the image by means of a focus detector. The focus detector, under computer control, operates a servomotor that moves the lens to the position of best focus. This procedure is repeated in several meridians and the measurements are analyzed by means of the computer which prints out the results in standard notation with a confidence factor which may vary from 0.10 in the case of difficult refractions to 0.90 if the results are highly repeatable.

A preliminary report on the clinical efficiency of the Dioptron has been published by the manufacturers, Coherent Radiation (1973). Two independent studies have been made by Sloan and Polse (1974) and Polse and Kerr (1975). Polse and Kerr demonstrated a high degree of correlation between instrument prescriptions and those obtained by means of conventional techniques. They estimated that the time required for the instrument to write a prescription was about 5 minutes per patient. Their results showed lower levels of accuracy in the case of eyes

with substantial amounts of astigmatism, especially if the axes were oblique. They found that the computed confidence factor is of only marginal value in predicting measurement accuracy. They draw attention to other limitations of the instrument. Measurement of residual ametropia through spectacle or other contact lenses is not possible because reflections at the lens surfaces create excessive noise in the detection system. Polse and Kerr conclude that the Dioptron is not a replacement for subjective refraction for the purpose of prescribing ophthalmic lenses or evaluating ocular health. An updated version of the instrument, Dioptron II, was released in 1978.

The 6600 Auto-refractor was introduced in 1972 and was developed from a patent for an automatic optometer filed by Cornsweet and Crane (1967). This optometer utilizes the principle of the Scheiner disk (Cornsweet and Crane 1970). The instrument is fitted with a device that automatically tracks the corneal reflection and maintains alignment during the measuring cycle. Satisfactory operation of this device depends on the patient being able to maintain reasonably steady fixation when his head is placed correctly in position. The refraction may be made with or without cycloplegics. An array of light-emitting diodes is used to display the current status of the refractive error in digital form at intervals of 3 seconds. This display permits the operator to judge the accuracy of the refraction. A hard copy of the refractive error may be obtained in a form that is easily convertible to standard ophthalmic notation. A clinical report on the instrument has been published by the manufacturers (McTigue and Cornsweet 1973). The sample of 15 subjects used in this study did not contain any strong hyperopes, anyone with high astigmatism, or anyone with known pathology.

In users' panel discussions the 6600 Auto-refractor was praised highly as a replacement for accurate retinoscopy and for the refractive examination of aphakics if the pupil diameter is larger than 2.5 mm. It was found to be unsatisfactory when moderately advanced cataracts or corneal disease were present; nor should it be used in the case of advanced corneal dystrophies. Some users claimed that the instrument had been used successfully over contact lenses. It was unsatisfactory when the patient was being treated for glaucoma with miotics due to the small pupil, and in cases of amblyopia with an alternating squint when the patient had eccentric fixation. Users emphasized the superiority of this instrument over retinoscopy in cases in which the image contour of the retinoscopic reflect is distorted. The Auto-refractor was found to be superior to keratometer readings in following the postoperative changes in refraction after cataract extraction.

The Humphrey Vision Analyzer is now available and represents a completely novel concept in eye refractors. It incorporates a complex system of variable-power spherical and cylindrical lenses. These lenses are the invention of Alvarez and Humphrey. A patent for their first variable power lens and system was filed in 1967 and accepted in April 1970. The principles of these lenses are disclosed in their patents, listed in the references below. The Vision analyzer is being manufactured by Humphrey Instruments Inc. of San Leandro, Calif. It has a continuously variable spherical range from +20.00 to -20.00 diopters readable in 0.12-diopter steps, with a continuously variable cylindrical range from +8.00 diopters to -8.00 diopters readable in similar steps. The cylinder axis may be incremented by intervals of 1 degree. The instrument costs about $25 000 (1977 prices) and allows the clinician to perform a subjective examination in significantly less time than by conventional procedures. Perhaps the most unique feature of this instrument is the elimination of all hardware in front of the patient's eyes during the measurement of the static refractive error.

Patents for a new telescopic optometer were awarded to Guyton (1972). The principles described in this patent have been subsequently developed by American Optical Corp. and have emerged as the SRIII Subjective Refraction System. This instrument combines the optometer principle with a co-axial system of movable cylindrical lenses to provide continuously variable spherocylindrical power across a spherical range of ±20.00 D and a cylindrical range of ±8.00 D. In external appearance the instrument resembles a vision screener. Its most novel feature is the split-level target system used for the detection and analysis of astigmatism. The patient is required to focus and align these and other simple targets by means of a knob at the side of the instrument.

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Chapter 4
COMPUTER-ASSISTED CASE HISTORY FOR EYE EXAMINATION

THE PRIMARY PURPOSE of an eye examination is not necessarily a prescription for lenses which allows maximum visual acuity, nor is it necessarily for one to relieve eye strain. Implicit in an eye examination is the search for insidious diseases, but even that may not be per se its primary purpose. The goal of an eye examination in our private economy, with free choice paramount, is the satisfaction of the patient. The clinician's aim is to satisfy his patient by doing whatever is necessary professionally to bring that about. It is correctly assumed that the patient wants to be advised of any present disease processes, especially if they can be arrested or reversed. It is often assumed that the patient wants to see as clearly as possible, but this may be an unwarranted assumption without confirmation.

A few patients, usually myopes, do not like sharp, clear images. There are many individuals who would choose less than maximum visual acuity if the alternative is wearing spectacles or even contact lenses. Normally, only the patient can make the choice between prosthetic optical aids, visual training, or even surgery with their costs, inconvenience, pain, and risks on one hand, and the status quo on the other. (In a military situation where the criterion is performance rather than satisfaction, maximum visual acuity may be assumed to provide the basis for maximum performance, for example on the rifle range.)

The case history gives the clinician the information needed to provide patient satisfaction. By disclosure of the patient's chief complaint or his reason for having an eye examination, the problem to be solved is often clearly defined. Secondary complaints yield further problems for solution if they can be solved along with the chief complaint and are not incompatible. In addition, any symptoms must be taken into account. The wishes of the patient, including economic and cosmetic considerations, are paramount. The case history reveals those wishes.

The case history, in addition to orienting the clinician towards the solution of the patient's problems, can also provide economy in the examination. Certain corners can be safely cut on the basis of data from the case history. However, other short cuts cannot be made without potential detriment to the patient. For example, visual field tests and ophthalmoscopy should never be bypassed because of the danger of overlooking disease, systemic or of the visual system. It is questionable, however, whether it is economically reasonable to perform extensive testing of the eyes' refractive system on a young adult with 20/15 vision and no complaints.* This type of patient, often seen in a university clinic, comes in seeking a "check-up."

There are certain key words or phrases in a case history that tell the clinician what the problem is even before all the data from the examination are in. An individual in the 4th to 5th decade in life who 'can't read the telephone book' or finds his 'arms too short to read the paper' obviously needs a convex-lens presbyopic correction to see clearly at near. A student who finds he cannot read the blackboard, especially if he sits at the rear of the classroom, is probably

*One of the reasons that ophthalmologists spend much less time performing general eye examinations than optometrists appears to be based on this principle. The ophthalmologist feels a minimum of data is adequate for patient satisfaction, whereas the optometrist often tends to believe in a maximum. Once pathological processes are ruled out it becomes primarily an economic matter, which presumably could be put to a test.

a myope who is going to need a concave-lens prescription for distance, and so on. Of course the eye refraction is still necessary, not only to determine how much spherical power is required for each eye, but also the cylindrical lens required to correct any astigmatism.

The case history gives the clinician the chief as well as secondary complaints of the patient. The clinician can gauge the strength of these complaints and the degree of the patient's desire to overcome them, and what he is willing to pay in cosmetic changes, inconvenience, money, and time for possible solutions to his problems. In automated eye examinations the case history is no less important. Although the computer may not yet be able to use all the subtle information extractable from the case history (because of the short cuts necessitated by the use of the computer), it is no less important than in manual examination. Any additional examination time usually costs the patient no more than his own time. Most patients do not consider their time as being as valuable as a doctor's, especially if they (rather than a third party) are paying for the service. With the development of subtleties in the flow charts, the time required for various parts of the computer-assisted examination should be reduced and approach that required for a manual examination.

The case history allows the clinician at the conclusion of the computer-assisted eye examination to accept, modify, or reject the recommended prescription determined by the computer, which can be programmed for maximum visual acuity. How well does the computer obtain the necessary information from the patient? The answer was obtained on a number of patients, first in a computer-simulated interview, in which the branching program questions were read from cards. Later, when the hardware and software became available, the actual computerized version was administered (Marg et al. 1972). Before discussion of our case history-taker, a discussion of medical studies in this field is appropriate.

Automated Medical Case Histories

Long before the advent of computers on the health scene it was recognized that the recording of a medical case history might be done in a way to reduce the time required of the physician. Various schemes have been used. Check lists have been given to patients to mark the indicated responses either alone or with the aid of a nurse-receptionist. Some of these lists could be automatically processed. One version uses questions printed on standard computer punch cards which the patient separates into two boxes, one for *yes* and the other for *no*. The cards are later fed into a card reader for batch computer processing.

In principle an interactive, branching program case history should be superior. Branching allows the flushing out of details of a problem as a human interviewer would do, with the skipping of the detailed questions that are not germane for a particular patient. Interaction with an on-line computer allows repetition of questions and fuller explanations where necessary. Warner V. Slack has pioneered in automated branching medical case histories. He generates the questions in printed form on the face of a cathode-ray tube. In addition to general medical interviews he has reported results on interviews for medical specialties such as allergy and gynecology. Slack and his colleagues (Slack et al. 1966, Slack and van Cura 1968, Slack 1969) find that the computer-conducted case histories are more complete than comparable ones obtained in the conventional way by a physician. The computer interview takes longer, but it is estimated that a comparably complete history taken by a physician would take equally long. Slack and van Cura (1968) report that the method is well accepted by patients. In fact, it was preferred to a clinician's interview by women taking the gynecological program because they felt less sensitive in responding to a machine about questions which if posed by a physician might embarrass them. Of course, initial acceptance can be biased by the novelty of the situation and the personal attention given subjects in an experiment, the so-called Hawthorne effect of industrial engineering.

Grossman et al. (1971) have analyzed a computer-based general medical interview program in regard to both patient and physician acceptance. Generally the patient accepts the method well but not the physician, apparently because he has been trained in a different way. The physician asks questions during an interview searching for the problem while making tentative possible differential diagnoses. While he may not be as systematic and thorough, he is all

ing while making alternative hypotheses in the course of getting to the heart of the problem. If he is handed a printout interview he still goes through this process. He may feel he is saving office time and is forced to use cold, second-hand information with a loss of nuances.

Although a number of companies have offered computer-based interviewers in the past, apparently none has survived, doubtless because of a lack of physician acceptance. Searl Medidata had a computer-based on-line multiphasic examination system incorporating a case history which is still in use around the country. It consists of a slide-presented carousel display (four to each slide) that allows up to about 300 separate displays of multiple-choice questions. The branching program is on-line as the first in the multiphasic test series. Although this test has been widely available, it has not (no more than the rest of the multiphasic examination) won general physician acceptance, in part because there is doubt that multiphasic examinations are cost effective. Our design of a case-history interview system for eye examinations (Marg et al. 1972) was based on the assumptions that the patient could not necessarily see to read (at least after the examination) and that he could not effectively use a teletypewriter keyboard. The questions were presented over a loudspeaker from a prerecorded audiomagnetic tape controlled by the computer. The patient responded by means of three pushbuttons on an answer box labeled *yes*, *doubtful*, and *no* (Plate B). Before the patient was seated at the loudspeaker and answer box, the operator typed in (via the teletypewriter) the patient's name, age, sex, occupation, and so forth. Initially the pushbutton box had an extra pushbutton to *enter* the response of one of the three buttons mentioned earlier. Later the entry button was eliminated, along with a small signal light which extinguished to indicate acceptance by the computer.

Each of the three buttons was used for different shades of meaning. The *yes* button also was used for 'sometimes.' *Doubtful* also meant 'don't know,' 'don't understand,' or 'repeat'. *No* could also mean 'not applicable.' This procedure differed from previous medical case histories in that the questions were presented in an audio rather than visual written mode. The advantage is that the interview could be given to a patient who was effectively blind or illiterate. A price paid for audio presentation was that only single questions could be asked at a time instead of the possibility of a half dozen questions presented simultaneously with a separate pushbutton for each answer. Another departure from past practices was the simplification of responses into three *yes*, *doubtful*, and *no* instead of separate responses for shades of meaning distinguishing between don't know, don't understand, and repeat. Multiple-choice questions which were simple with a multipushbutton slide display were not possible here. The decision for the simplified audio system was also influenced by the greater simplicity of the hardware available at that time, which was built with a standard solenoid-operated reel-to-reel or cassette tape recorder.

Hardware

The system was controlled by a Digital Equipment Corp. PDP-8/E, although initially a PDP-8/I was used. The computer I/O equipment included a teletypewriter, a two-track stereo reel-to-reel tape recorder which was solenoid operated, and the response box described earlier. The response box was interfaced with the computer through the static input buffer. Although the programs were stored on a magnetic disk, this storage mode was used for convenience, since the final system was planned without it. A disk would be needed only if multiprocessing or timesharing for more than one interview at a time were to be developed. The core memory consisted of 4K 12-bit words and a 1.5 μsec memory access time. The static input buffer and the static output buffer each used three of the 12 bits available.

The vocally recorded questions were on one of the two parallel tape tracks; the other carried prerecorded pulse sequences for control of the tape positioning. The sequential binary-coded absolute addresses were spaced at about 0.5-sec intervals. These addresses were converted to digital form and used in a control procedure which allowed the positioning or repositioning of the tape at any desired address. The operation of the recorder was initiated through the static output buffer which could select four states, namely, *play* (slow forward), *reverse* (fast backward), *fast forward*, and *stop*. The verbal messages were recorded in the sequence of the branching program and access was generally accomplished within a few seconds after the last response.

PLATE B Automated case-history interview

Computer Program

The final output of the program produced a list of positive and negative responses describing the patient's visual status (Fig. 4-1). The inputs were the question list, the algorithms for processing the questions, and the on-line responses of the patient as the interview proceeded. The coded list of answers was organized for use in coded form as input to subsequent parts of the eye examination and also expanded text form as a narrative or summary outline case history for the clinician.

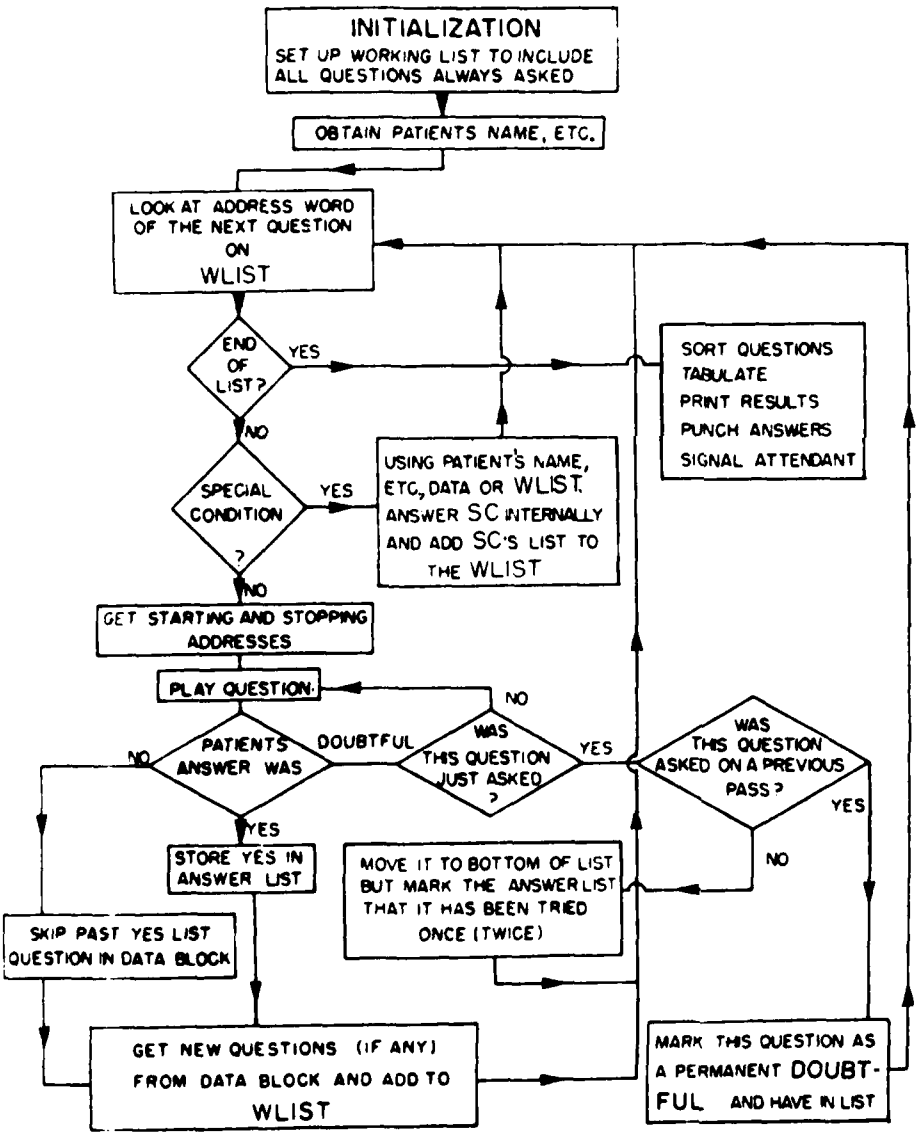

FIG. 4-1. Case-history flow chart.

The branching program was initially set up with two lists. One consisted of all the questions along with pertinent information about each question such as its location on audio tape and sublists of questions to follow dependent on the patient's response. The other list consisted of basic questions which were invariably asked. It formed the basis for departure in operating the program.

The control program updated the original list of questions forming a working list. Associated with each question was a *yes list* and a *no list* composed of the question numbers to be added to the working list in the event of a *yes* or *no* answer. The working list grew during the run starting as the initial list of questions. Later it became the list of questions still to be asked, and finally a record of those asked. The *yes* and/or *no* lists would be empty for nonbranching questions. They served to obtain the required data but did not alter the question flow.

Operation

At the beginning the patient was instructed by a recording over the loudspeaker on how to respond to the questions. When the *doubtful* button was pressed the question was repeated. The program moved on to the next question following three doubtful responses after storing the appropriate number. After the dynamically up-dated working list of questions was completely processed, the program presented once more any of the missed questions. Any answers would be used to update the working list.

The Case-history Interview Program

When our work in this field was started we could find no systematic study of case history questions in eye examinations. A few textbooks give some generalities based on the clinical experience of the author, but no experimental investigations were found in the literature. We, too, had to use clinical experience as our guide.

The program, which is shown in Appendix I, consists of almost 200 questions. They are organized into a branching program where the patient's response to a question determines the next question to be presented. Some of the questions are generic ones. They raise a general question which if answered affirmatively elicits a series of clarifying and quantifying questions on subtopics. If the basic question is answered negatively, all the satellite questions under it are skipped. Some of the major generic questions are: Are you troubled in any way with blurred vision? Have you headaches, eye pain or eye strain, or fatigue? Do your eyes burn, smart, itch or tear, or otherwise feel irritated? Have you ever had crossed eyes or an eye that turned out? Are there other abnormal things about your vision that bother you? Have you an eye disease? Are you at present under the care of a physician for anything? Do you wear contact lenses? Have you ever worn glasses to correct your vision? Do you want spare glasses or special-purpose glasses?

The questions should not be considered fixed and final but as a base from which to make modifications, especially expansions. Different populations may require different questions or at least different emphasis and phraseology. Even common attitudes of the times can give different connotations to words that can distort the intended meaning.

Clinical Trials

Before the hardware and software were available, a preliminary version of the questionnaire was typed on file cards and administered manually to 53 clinic patients. The patients were asked the questions verbally, following the cards in the branching program in a manner simulating an automatic interview. The patient's responses were restricted to the three pushbutton answers. This shakedown trial proved to be valuable because the need to change the phraseology of some of the questions became obvious. Connotations of words were sometimes critically important. For example, initially the patient was asked if he was taking any drugs. In a university community during this period, drugs could mean not only chemicals in the pharmacopoeia but also hallucinogens and narcotics. The question was modified to ask 'Are you taking any form of medication?'

Another point that seemed obvious after the fact was discovered from the preliminary tri- . The human clinician has no hesitation in asking a patient if she is pregnant. He does not that in posing this question he is making at least two decisions that must be explicitly pro- ammed in an automatic system: (1) the patient is female, and (2) she is of childbearing age. The first is simple, since even if it should not be visually apparent, there is no reason that the ori- entrance information on the patient's age and sex should not be noted correctly. The second requires more judgment. Biologically childbearing age spans the 12th up to about the 50th . However, there may be some reluctance to ask a 12-year old girl the question since the first pregnancy in our society has commonly come after 16 to 18 years of age. Similarly, at the other end of the scale it might be considered ungallant not to ask a postmenopause patient the question, provided she is short of being octogenarian.

The improved version of the questionnaire was recorded on tape and was administered to patients who volunteered for the additional interview. The same patients were also inter- ewed by clinicians who did not know that their case histories were being compared with those ken by computer. The results of the two series were compared and judged on the following characteristics: (1) completion time, (2) determination of chief complaint, (3) determination of secondary complaints, (4) strength of reported distress, need, desire, and (5) patient understand- g and education.

Interview Time

The automated case history averaged a completion time of 25 minutes with a range of 15 42 minutes. Part of the time was lost in waiting for the next question, especially when the sys- m had to search for a question which was out of the order of normal sequence. This problem be overcome by improved hardware. The only limitation in this regard is cost. Two or more recorders can be used so as to be ready to play as soon as an answer to the previous question is signalled. Speech-synthesizing techniques or multiple-track recorders can be employed but their current costs are too high for some 200 questions if one is to have a reasonably economical sys- m. Currently 16K bits of memory are required for each second of digitally based speech. This is not an economic approach for long messages, but new developments in speech synthesis point to less expensive solutions in the near future.

The length of time required for the automated case history can be reduced in other ways. Visually presented multiple-choice questions are faster. The fact remains, as has been shown in the medical interviews mentioned earlier, that automatic systems devised to date intrinsically take longer because they do not take full advantage of the shortcuts taken by a clinician and they are more complete. It can be argued that they are unnecessarily complete but it can be countered that it is worth being thorough in the health field where the significance of data is not always immedi- tely apparent.

Our taped automatic system was relatively slow between questions. In the worst case it took almost a minute, but that was not typical. The average question with 12.8 syllables took 4 sec to present, and the response took 1.8 sec. When the patient had difficulty responding to a question, the time averaged about 11 sec with a range of 4 to 25 sec. The overall response time was 5.8 sec, which is close to the 7-sec response line reported by Slack et al. (1966).

Versatility

The program can, of course, be lengthened or shortened. It can be lengthened by the addition of questions to bring out finer shades of meaning, or it can be shortened to take less time.

If it were easily possible to prejudge the intelligence of the patient, more than one ques- tionnaire could be used. The administration time and the completeness of the interview could be improved with a higher intellectual level of questions. It also might be possible to reduce the time taken for the interview by the use of physiological responses rather than voluntary responses via pushbuttons. These responses might include reaction time and heart-rate (Slack

1971) as well as respiration and galvanic skin response. This approach was tried by Hung and Marg (1973) and the data were found wanting. Only the eyelid blink had any predictive value, but it was not predictive enough to be used in a practical system. Multiple-choice questions could reduce the time required but it is not practicable to present such questions verbally.

Chief Complaint

In three cases out of twenty-seven the computer failed to determine the chief complaint (reason for coming). The first example was a student who wanted the experience of an eye examination since he was contemplating entering optometry school. The second returned after a previous examination in the clinic in response to being told to return at a later date to have his fundus reexamined. The third patient arrived because he had experienced transient amaurosis.

None of these reasons was covered in our questionnaire at the time. The student who simply wanted the experience had an extraordinary reason, but the other two should have been identified. Subsequent versions of the case history include many more possibilities, but no doubt further unforeseen complaints will surface and appropriate questions will be needed. Such omissions do not invalidate the automatic methods since the number of programmable questions is virtually unlimited. For improved coverage, experience will be needed with particular groups of patients who are to be served in their normal environment. Easy editing of the program is thus an important part of any system, requiring a high-level computer language.

Secondary Complaints

The computer elicited 131 secondary complaints, or an average of 4.3 per patient. It was superior to the clinicians perhaps because they did not bother to seek them or did not bother to record those they heard. Thirty of the secondary complaints had to do with asthenopia.

In some instances the secondary complaints were not supported by the actions of the patients, which indicates a lack of validity. For example, 90% of the patients mentioned desires for new ophthalmic materials such as lenses, frames, and contact lenses, but most patients when questioned verbally did not want to purchase such materials. Apparently the attitude lacked monetary support.

Twenty secondary complaints were discovered by clinicians that the computer system failed to identify. Eleven of them were missed because relevant questions were not included in the system. Three involved the names of drugs and one an illness which could be typed in on the teletypewriter but not easily fitted into a branching program of reasonable size. If more questions are available, there is less possibility of the patient becoming frustrated because he feels he is not getting his message through. However, too many questions would require too long a period of patient-machine interaction.

Distress, Need, or Desire

An important aspect of the eye examination which is mastered by the human clinician is the gauging of the importance of the complaint or desire reported in response to questions. For example, a patient who says he would like contact lenses must be carefully questioned to determine whether he wants them enough to warrant the expense, nuisance, and transient discomfort of fitting. Patients may say their eyes are irritated from reading, but the distinction between an actual source of discomfort and a relatively unimportant complaint must be made. The human interviewer looks for signs of the strength or severity of the complaint. He may find them in verbal as well as nonverbal behavior during the response. These cues are denied to the computer. It may be possible to use polygraphic (lie detector) techniques to clarify this point, but our experience with these methods do not encourage us in this regard (Hung and Marg 1973). A human interviewer draws out the patient. He points out the costs and inconveniences of contact lenses, and asks if the eye irritation is severe enough to make the patient cease reading or sewing. Similar questions would enable the computer system to analyze patient responses in the same way and should be used in these programs.

Understanding and Education

The human clinician, depending on time and inclination, answers the patient's questions as he tries to give him a better understanding of various concepts in relation to his visual function. This process includes explaining words or concepts unfamiliar to some patients. Such terms as *glaucoma*, or alternate terms such as *ocular hypertension*, are often not understood by the patient. It is possible to program the case-history taker to give explanations of these terms if they are not understood. For example, following a doubtful response to the question Have you glaucoma or ocular hypertension? a further and detailed explanation could be available before it reverts to the original question for another response. The computer would tutor the patient as the human interviewer does when he has the time, patience, and inclination.

Conclusions

The computer case-history taker works. In an ophthalmic examination, case-history taking by a doctor is generally very short. The computer generally takes more than 15 minutes. It may be questioned whether it takes the doctor as long to go over the printout of the computerized case history as it does to take it *de novo*. In other words, is the computerized case history cost effective? It clearly would not be if the patient's time were considered as valuable as the doctor's. One must not forget in the equation of evaluation that a computerized case history provides a valuable printout. The patient's record is stored safely in the databank, ready for review every time it is recalled. Completeness, thoroughness, rapid access, and excellent legibility are certainly worth considering. However, unlike the case for cost effectiveness in computerized subjective eye examination, that for computerized case history has yet to be established.

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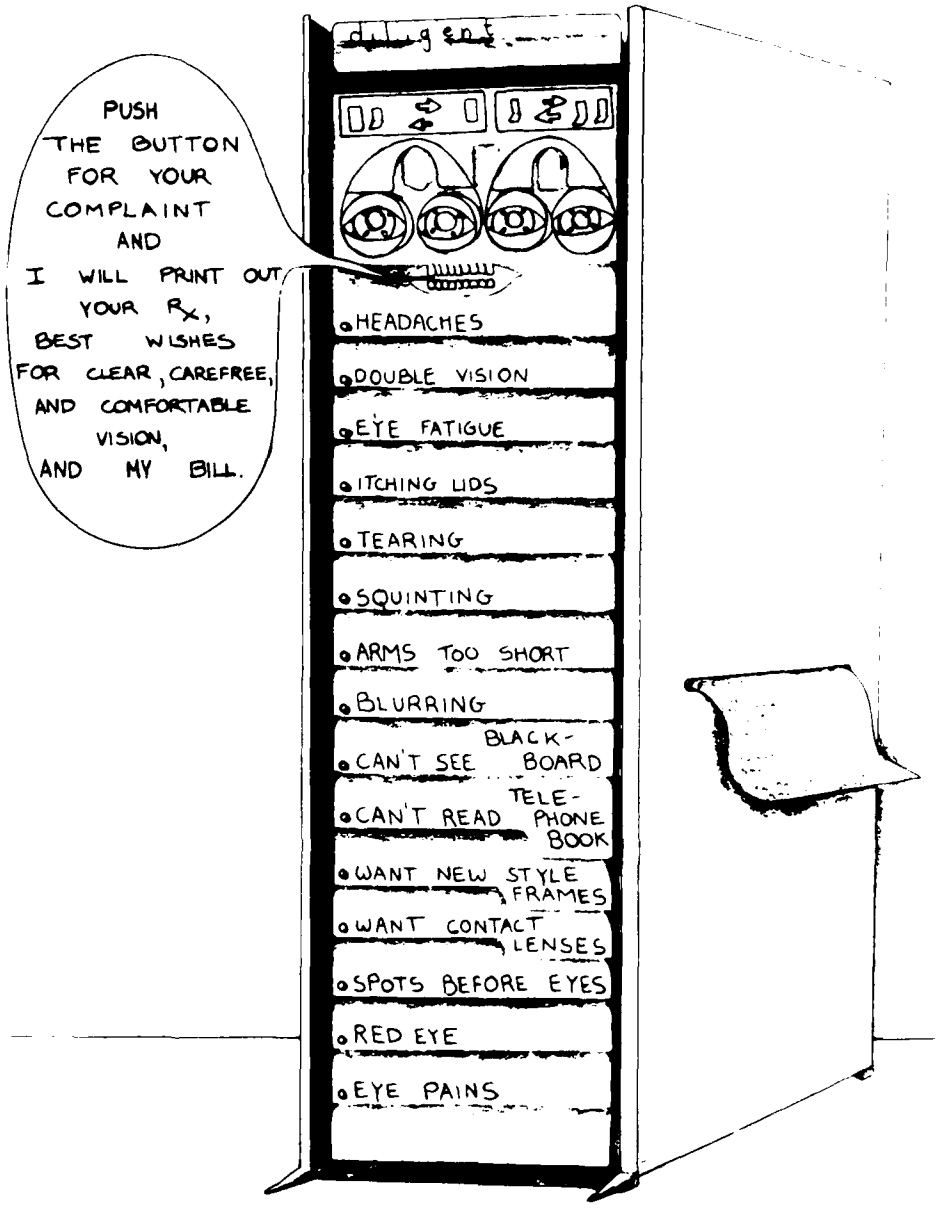

PLATE C. Artist's concept of automated eye examination.

Chapter 5

EXPERIENCES WITH MODULAR EYE EXAMINATION

Robert D. Reinecke

PURPOSE. The purpose of this chapter is to outline my experiences in developing a modular [illegible] unit, both positive (benefits) and negative (disadvantages). The general thrust [illegible] should be applicable to any large-scale eye-examining facility where maximum [illegible] trained professionals needs to be meshed with efficient utilization of the most [illegible] especially when the operation functions in a preplanned manner.

[illegible] data collection and its use are described. Guidelines must be set up by all health professionals as to who sees what kind of patient based on this type of data. In most [illegible] decision would be that the ophthalmologist would see all potentially diseased [illegible] optometrist would take care of all refraction devices and problems, and patients with [illegible] eye disease would be returned to the general practitioner. The triage formula[illegible] here is one that was used in such a setting at the Harvard Community Health Plan, [illegible] was gleaned from this type of operation. It is essential that optometrist and [illegible] agree on all types of triage back and forth between the two groups of professionals [illegible] patient will be undertreated in any way. Other means of triage can doubtless be [illegible] detailed. Those expressed here were in complete accord with the professionals [illegible] particular setting. In most prepaid health groups, both the optometrist and the [illegible] have an overload of patients and there will certainly be no competition between [illegible] for additional patients.

[illegible] This should be clarified at the outset. The first is the term module, which will be [illegible] by subsegments of the complete eye-care unit. For example, an automated [illegible] device would be considered one such module, a refractometer another. The second [illegible] distinction between data collection and decisionmaking and delivered services. This [illegible] appear obvious, however, medical literature and State laws relating to professional [illegible] are very hazy in this regard. Many States have specific features in their laws that [illegible] collection of one kind of physiological data as examples of medical care, whereas other [illegible] physiological functions are regarded simply as data collection and no further [illegible] them.

[illegible] disregard these legal considerations, since in most instances either an ophthalmologist or optometrist will be in the immediate vicinity supervising other activities, so that, general data collection is involved. However, it is important to distinguish among the [illegible] conceptually. The more objective the means of collecting the data, the more [illegible] to have data collection under the direction of a lesser-trained individual. On the [illegible] *the greater the degree to which* a particular form of data collection is uncertain or an [illegible] certain it is to demand a highly trained individual to make that data collection. In [illegible] most of the data collection having to do with eye care can be sufficiently systematized to [illegible] be done by minimally trained personnel. However, that does not in any way reduce [illegible] for highly trained supervision of such data collection to insure adequate quality control, [illegible] discount the degree of training required for competence in analysis of the data.

The second item worthy of clarification is that health-maintenance organizations are obviously geared to effective utilization of the concept of modular eye examination. In fact, much of my own experience in modular examination was obtained in such a setting. Health-maintenance organizations are not a new concept. Basically they are prepaid health-insurance schemes of the sort that have been in operation for many years but recently have been popularized under the term health-maintenance organizations or HMOs. However, prepaid insurance schemes are not synonymous with HMOs, for large prepaid health plans have considered and will consider HMOs as means, separate from themselves, of centralizing the health-delivery services to their members. Our modular-examination experience seems applicable to both the prepaid insurance and HMO settings. But that does not mean that the modular concept is always appropriate or most economical for either prepaid systems.

The main advantages claimed for HMOs are their cost effectiveness and their guarantee of availability of services to the user at a set prepaid fee. The usual strategy is to employ physicians and to make every attempt to increase the efficiency of these doctors by generous use of paramedical personnel. The model of nurse practitioners in the pediatric clinic is such an example. In general, use of these paramedics has proved to be useful, particularly in working with healthy children.

In the HMO's consideration of eye care, then, economic factors are of primary importance. Since the salary scales for ophthalmologists, optometrists, opticians, technicians, and nurses vary in proportion to their training and experience, the planners of the HMOs typically wish to maximize the talents of the lowest-paid individuals. Yet the planners of the unit must also provide *medical and surgical eye care as well as other eye services* to the group. Thus, an ophthalmologist is often the first of the eye team to become employed by this type of group. At the outset, the ophthalmologist can take care of a reasonable patient load. Typically, the eye clinic load in such an institution grows rapidly and the increased demands placed on it require planning for expansion to be made and implemented. In this chapter, I shall try to outline some ways in which modular eye examinations have been found to be helpful in such a situation.

Automation is certainly an important consideration in setting up a modular unit. Some observers consider automation and economy as synonymous. Experience does not bear them out, as we shall see.

Outline of the Problem

When we conceptualize the eye examination into modular steps, we have two basic goals in mind: (1) on the basis of various modular stations, the patient must be triaged to the most effective professional for final analysis of the data; and (2) when the patient reaches that professional, the data must be readily accessible so the professional requires only a minimum of further data collection before decisionmaking and treatment or other services are undertaken.

Let us then consider five typical modules: history taking, visual-acuity and stereopsis measurement, visual-field measurement, *refraction measurement, and intraocular pressure determination*. The reason for considering these modules first is that many devices have been developed to test these parameters that make them particularly suitable for consideration as modular units, and they are also pertinent for operation by technicians rather than professionals.

1. History-taking Module

It was our goal to develop a history-taking device that would be compatible with our data-to-storage and data-displaying device. It turned out ultimately that our preoccupation with this device and other aspects of automation was actually a mistake, but a brief review of the attempt illustrates some of the less-than-obvious problems involved.

A cathode-ray-tube (CRT)—i.e., television-like—display was used to show in sequence a series of history-taking questions for the patient. The sequence was developed via a branching technique, in which positive or negative responses to a question would lead the computer to select the next appropriate question or proceed to the next logical consideration of the history.

Several devices currently on the market utilize various means of presentation of this type of queries to a subject. Obviously, if a patient has serious visual problems it might be appropriate to have these questions available in the audio format as well. (Anyone who has had experience in any eye clinic, however, would recognize that the majority of patients have relatively good vision in at least one eye; hence, the audio format is not a high priority.) What initially prompted us to use the CRT was our concern with the objectivity of the history taking. Our enthusiasm was quickly dampened, however, since we found that it was necessary to have the patient guided through the use of the device by the technician in almost every case. Teaching the patient to use the device on his own was an unproductive didactic venture since it was a one-shot effort for the patient. In the final analysis it was quicker to have the technician simply guide the patient through. If an HMO has a large series of history-taking devices used on a repeat basis throughout the entire facility, so that one is assured of repeated use by the same patient, then perhaps the time spent teaching the patient to use it would be justified.

After we completed these experiments with the CRT method, it became apparent that the use of a written format would be just as appropriate and certainly much more economical. A technician could just as well guide the patient through a series of written questions. Appropriate checkmarks could be used to indicate positive or negative responses and a branching technique could be accomplished just as easily. In such a written format the process is somewhat lengthier, but the net result is immediately available (as opposed to problems of access to a limited number of computer terminals), and no computer expense is involved.

If a computer is being used, a variety of clever techniques can be utilized to make the data collection neater. However, these techniques do not greatly increase the efficiency of the procedure. For example, one could, after the automated refraction is done, have the near visual acuity measured without any near-add and again with the near-add, if warranted by the patient's age. The decision as to the amount of add would be dictated to the technician by the computer according to the patient's age and occupation.

What subjects need to be covered in a history? Most books on eye examination detail them in a complete fashion, or a list could be developed by any knowledgeable ophthalmologist or optometrist. Obviously information such as the patient's name and identification number appropriate to that clinic (which in most instances is the Social Security number), address, telephone number, and birthdate should be included. Answers to a query as to what visual complaints are present can be broken down so that a checklist of no more than five or six accounts for almost 90% of the chief complaints. A series of questions pertaining to the general health of the patient would be particularly useful to anyone doing an eye examination and would note such factors as a history of diabetes, drug allergies, heart disease, signs and symptoms of brain tumors, headaches, and diplopia. Items such as specific drug allergies would be displayed prominently or flagged on the history. Items indicating a medical problem would automatically direct that patient for ultimate triage to the ophthalmologist rather than the family practitioner or the optometrist. A short family history should also be taken, particularly in regard to a family history of glaucoma, strabismus, or cataracts. If the patient is a child, then other items are also appropriate, including birth weight, history on convulsive disorder, developmental problems, reading problems, or specific defects for which the parent might be expected to have some concern in the final discussion about disposition of the patient.

2. Visual Acuity and Stereopsis Module

Many attempts have been made over the years to automate the measurement of visual acuity. None of them has met with outstanding success. The most effective method still seems to be to teach a technician how to measure visual acuity. However, the method developed by Crossman, Goodeve, and Marg (1970) and applied by Marg and also by Decker et al. (1975) may be an exception. Even that has distinct limitations, for the astute clinician would certainly be able to learn many things by measuring the visual acuity himself. If the patient has 20/20 vision through his present prescription, that fact comprises a significant item in the triage of patients, for

reasons we shall review below. If the patient has not 20/20 vision but can achieve 20/20 with the pinhole visual-acuity test, that too is significant in the triage process. Quality control is particularly important in the visual acuity module. The technician often tends to report good visual acuity when less that that exists, or else may not encourage the patient to make efforts toward good visual acuity which he could easily obtain with a minimum of encouragement.

At this same station or at the refraction station, it is usually appropriate to have the patient's glasses carefully measured. That can be done automatically with some of the new refracting instruments, but in any event a technician can easily be trained to obtain most of the significant data from the patient's old glasses. Once again an astute clinician could learn much more by measuring them himself, but one cannot ordinarily afford this luxury in this type of patient management.

At the time of my experience in setting up a modular eye unit, stereopsis measurement was not utilized as a routine screening-test medium owing to its apparent lack of reliability in such applications. Since that time, it has been found that when an appropriate stereo test is used, such as the Random Dot E, stereo-based visual screening is, in fact, very reliable, especially for detecting amblyopia and the more serious ocular motility problems. (This particular test is noteworthy in that it can be used with young children whom it is often difficult or impossible to test reliably with most visual-acuity measures.) Thus, stereo screening should be included along with visual-acuity testing in this module, by means of a reliable stereo test such as the Random Dot E. Indeed, it is not only feasible but would be useful—in view of the ease of use and reliability of the Random Dot E type of test—for other members of the health-maintenance organization or other facility with which the eye care unit is associated to do this screening as well. In view of the importance of early detection of motility problems in children, local pediatricians and family practice physicians should also be encouraged to do stereo screening.

3. Visual-field Measurement

Every patient tested in this setting should have his visual field measured with the best equipment available; otherwise, in our experience, significant pathology may be overlooked. With this in mind, it should be noted that all the present-day automated field-measuring devices have limitations. The manager of such an eye-care facility must insist on quality-control checks. From time to time a patient with a known visual field defect should be sent through the system in an unidentifiable or nonflagged manner to provide a check of the technician's skill. The available field-measuring instrumentation is generally good; in our experience, automated field devices virtually unfailingly detect significant pathology. Patients past the age of ten or so usually cooperate in the use of field-measurement device and typically they enjoy it.

Any field defect that is noted is used to flag that patient as an appropriate referral to the ophthalmologist after all the data collection is done. (The patient should complete the basic set of modules whatever his disposition.) Thus, the decision for triage is not made until the last step, in the present example, after the intraocular pressure measuring station.

Many patients have some apprehension about not being examined totally by the clinician. High-quality automated devices go a long way toward relieving this apprehension and replacing it by the feeling that the patient has had the latest in data collection. Moreover, most patients believe they should not waste the professional's time by having the professional collect data. The patients have achieved this understanding before most professionals have.

4. Refraction Substation

At the time of our experience, automated refractometers were still very much in the prototype stage. We tested one or two such prototypes and were duly impressed with their productivity, but I have had little personal experience with their use in this particular setting. I am nevertheless enthusiastic about them and believe that anyone setting up such a modular examination unit should seriously consider obtaining one of the automated refractometers as a primary element. Thus, all patients should if possible have refractometer findings, which should be clearly entered in the data sheet that accompanies the patient through the several modules. If some sort of centralized computer data collection is used, the input must be immediate and all the data collected up to each point in time should be readily available to any examiner.

It would be extremely useful if the patient could be refracted both with and without

glasses on the refractometer. It is easy to write programs for computers to calculate net refractive errors with appropriate input of the patient's spectacle correction worn during the examination. Whenever the patient wears lenses of over +4.00 it would be particularly helpful to have the refraction done over the patient's glasses, so that precise determination of the new glasses could be achieved without any further consideration of the vertex distance and other variables. However, present-day refractometers usually cannot be used to refract through the patient's glasses.

Although we have been terming this station the refraction station, functionally it is only a refractometer station. "Refraction" comprises a specific professional task, namely that of using the optical data collected at this point to decide whether further refinement is appropriate or whether the data suffice for the needs of that patient and no further attempts at refraction need be made that day. We touch on this point further when we discuss the refractionist.

Intraocular Pressure-measuring Module

Several devices now on the market give accurate IOP data if used in the recommended fashion by a well-trained technician. This is actually the perfect setting for such a device, in which one can assign one or two technicians to use the same device repeatedly. Such technicians can become extremely proficient in the use of the device, though again careful quality control must be maintained to insure that such technicians are performing optimally day after day. The more sophisticated the instrument, the more it is designed for ease of use and thus the greater the temptation to use even less trained individuals than previously. Although such individuals can become proficient in the technical use of the instruments, they usually have little or no sense for inappropriate findings. We found that such minimally trained technicians were very strongly tempted to find readings always within "normal" levels. They are, of course, alerted to the immediate triage of certain patients on a priority basis. Thus, patients with a pressure of 50 mm Hg are immediately sent on an emergency basis to the ophthalmologist. But the technician is occasionally embarrassed to find that inappropriate levels of pressure were reported when the patient actually turned out to be within normal limits. This embarrassment results in a bias in the direction of under-referral and increases the temptation to read all levels of pressure as within normal limits. This tendency has to be carefully and consistently counterreacted, once again by effective quality-control measurements (such as sending a patient of known abnormal IOP through the module). It may sound monotonous to keep reiterating the importance of quality control, but it cannot be overemphasized in a modular context. This fact was repeatedly demonstrated in our experience. Lack of such control fundamentally undermines the whole concept of a modular examining unit. However, if the manager of such a unit is carefully oriented toward appropriate encouragement of the technician, and toward always avoiding any embarrassing situations with regard to over-referral, the "normal" bias can be avoided and the module can be expected to function in an effective and productive manner.

Triage of Patients

Up to this point in our modular examination, we have collected the data on the patient's history, visual acuity and stereo status, refractometer data, visual field screening, and intraocular pressure. This is sufficient information to triage the patient to the ophthalmologist or optometrist. In such a setting this triage is the most logical means of division of responsibility. The triage of all patients with medical problems should be through the ophthalmologist; that is, the patient should not be bypassed, say, to a neurologist, internist, or other professional until the ophthalmologist has seen the patient. At this point, when the data are reviewed, a series of predetermined referral paths that are clearly understood by all the professionals involved are to be followed by the technician screening the data. Certain positive responses in the history taking (such as pain in the eye, double vision, haloes about lights, and floaters) are obvious measures for direct referral to the ophthalmologist. Such patients could certainly be seen first by the optometrist if that were the decision of the eye-care team; but in our experience, the optometrist would generally refer such patients back to the ophthalmologist, so that it is more advantageous in this setting for the ophthalmologist to see these patients first. Other formats can certainly be employed. For example, the optometrist might see all the patients before triage; or the ophthalmologist might see all patients first. Available personnel and the prior agreement would obviously

dictate the triage criteria. In response to a simple plea for a change of glasses the normal referral would not be to the ophthalmologist but to the optometrist, provided there is no medical finding in the history that would obviously refer the patient to the ophthalmologist. Since many medical conditions may affect the refractive status of the patient, it is inappropriate for the optometrist to refract these patients prior to the medical clearance. Basic refractometer data already present should become a significant feature in the diagnostic data appropriate to that patient, such as in the case of the refractive status of the diabetic or anisometropia in a patient with a field defect.

Visual-acuity data may be used in a similar fashion for triage. There is no general agreement among professionals as to the definitive referral of patients on the basis of visual acuity. However, in the present setting it makes sense, since all professionals in a modular unit are likely to be busy and the most effective triage that can be achieved would probably be based on this simple finding. Once again the availability of personnel and prior agreement among the eye-care team must dictate triage criteria. The following plan of triage we evolved may or may not be appropriate in other circumstances. Whenever the pinhole visual acuity was less than 20/25 the patient was triaged to the ophthalmologist. If the best visual acuity obtained (including pinhole) is 20/25 or better and no other indications for referral to the ophthalmologist have been found, then this patient, in my opinion, should be referred to the optometrist. Any visual-field defect found was also cause for triage to the ophthalmologist.

It goes almost without saying that the triage system can be overridden by any of the professionals in the group at any time when that is deemed to be in the patient's best interest. For example, the ophthalmologist may often wish to discharge a patient from his care for, say, one year; yet he feels it is appropriate for the patient to have a final refraction in 6 weeks. Such a patient would be asked to go through the basic modules and would then be triaged to the optometrist (rather than to the ophthalmologist as his data collection would otherwise indicate). In similar fashion, an optometrist might see some questionable condition that he felt was not yet an urgent problem but was of sufficient concern to justify asking the ophthalmologist to see the patient in, say, 2 or 3 months. Such a patient would be asked to come through the modules and then be triaged to the ophthalmologist even though there was otherwise no indication that such a triage was necessary.

Intraocular Pressure Measurements

Generally, if the pressures are over 22 mm Hg, the patient should probably be triaged to the ophthalmologist, although experience with the technicians, testing device, and patient age group under consideration might vary this criterion in a particular setting. Are we suggesting intraocular pressure measurements for all patients? Yes, that is the case. All patients who can cooperate in having an intraocular pressure measurement should be encouraged to have it done. If screening devices are to be used in our modular system, they must be used consistently and on as wide a base of the population as possible; otherwise, underreferrals will creep in and reliability will be impaired.

Refracting Substation

Refractive data are not used as a means of referral in most instances except on the basis of prior agreement or personal wish of one of the professionals involved. For instance, a clinic might decide that all aphakic patients who come through the first time or any myope over eight diopters should be referred to the ophthalmologist. Such policies are individual matters to be decided by the ophthalmologist in consultation with the other members of the visual-care team.

If the patient is an asymptomatic individual who for some reason wants a routine eye examination and proceeds through the basic modules without any significant data being accumulated that would suggest referral to the optometrist *or* ophthalmologist, it would be entirely appropriate to refer this patient back to the family-care physician. It may be difficult for eye-care professionals to agree with this procedure, but experience shows that with strict adherence to the procedures that have been discussed, almost no significant ocular-pathology cases will be missed. One must assume that the other health-care professionals in the entire medical organization will be doing funduscopy examinations on a regular basis as part of their general physical examination. Thus, some professional consideration must be given to these people and such consideration will greatly reduce the patient load to both the optometrist and ophthalmologist. Many patients, how-

ever will have complaints such as "I want my glasses checked" or "I want a new pair of glasses." Such patients, with no need for referral to the ophthalmologist, would proceed to the optometrist. At this point, he would probably utilize the history and data to do a refraction to ascertain what final prescription should be given. Since the module data are readily at hand, his determinations can be made quickly and efficiently in most instances, unless specific problems are found. Further data collection may be appropriate to the needs of the ophthalmologist or the optometrist, according to their personal standards. It turns out that the more esoteric the data that are desired, the more easily they can be *usually* measured in an automated fashion. For example, points of convergence can easily be automated on various eye-movement tracking devices; so can optokinetic nystagmus, color testing, and stereopsis.

If a computer is available for calculations, the final refraction check may well be done with the patient's old glasses in place. If a refractometer has been used, the patient's old glasses usually will have been measured in an automated fashion. These data, coupled with the refraction over the glasses, can be utilized by a computer to calculate the final prescription in a reasonably fast and easy fashion. Once the refraction is completed and any other eye problems have been handled by the optometrist, the patient may be triaged to the optician.

Any form of quality control and management can be effected by the agreement of all the professionals in the organization. Let the ophthalmologist be responsible for quality control of the history taking, intraocular pressure, and field testing; and the optometrist, for quality control of the visual-refractometer and visual acuity-stereopsis modules, as well as quality control of the optician's services. Some patients will be triaged directly to the optician. Such patients will have perhaps broken their glasses, or pass through the modules without any evidence or need for triage to the ophthalmologist or optometrist.

In summary, the eye examination can be divided into various modular units. The data from these examinations can be used to triage the patient appropriately to the ophthalmologist, the optometrist, the optician, or back to the family-practice physician. Such a system would seem to be optimally efficient and make maximum use of each individual's particular training. Such a system, in general, is expensive to operate; modularization is not indicated if the patient population is small, rather, the most effective arrangement is for the ophthalmologist, optometrist, and optician to work on a carefully controlled person-to-person basis in a way conducive to the best patient care.

The above experiences are dictated in large measure on the basis of experience with this type of eye-examining facility used over two years at the Harvard Community Health Plan. The unit ceased operation after a bad fire destroyed the resources. The system was not operating on a sufficiently sound fiscal basis to warrant starting the unit up again at that time. Part of the unit's operation was to be that of a data-collection laboratory for the use of the general ophthalmologists in the Boston area. However, they did not make use of the facility for data collection in sufficient numbers to warrant its continuation for that reason.

Some of the triage procedures mentioned in this chapter may be considered controversial by some optometrists and ophthalmologists. Whenever we had an opportunity to discuss appropriate patients for referral between ophthalmologists and optometrists in fairly large committees on which both groups were adequately represented, the final opinion for cross referral was generally along the lines emphasized in this chapter. I fully understand the sensitive nature of this type of problem. One can only admonish all planners of eye-examining facilities to keep the patient constantly in mind and to cross check repeatedly the quality of the eye care service that they are delivering, so that patients with eye disease will not be overlooked and the full utilization of all health professionals be maximally attained.

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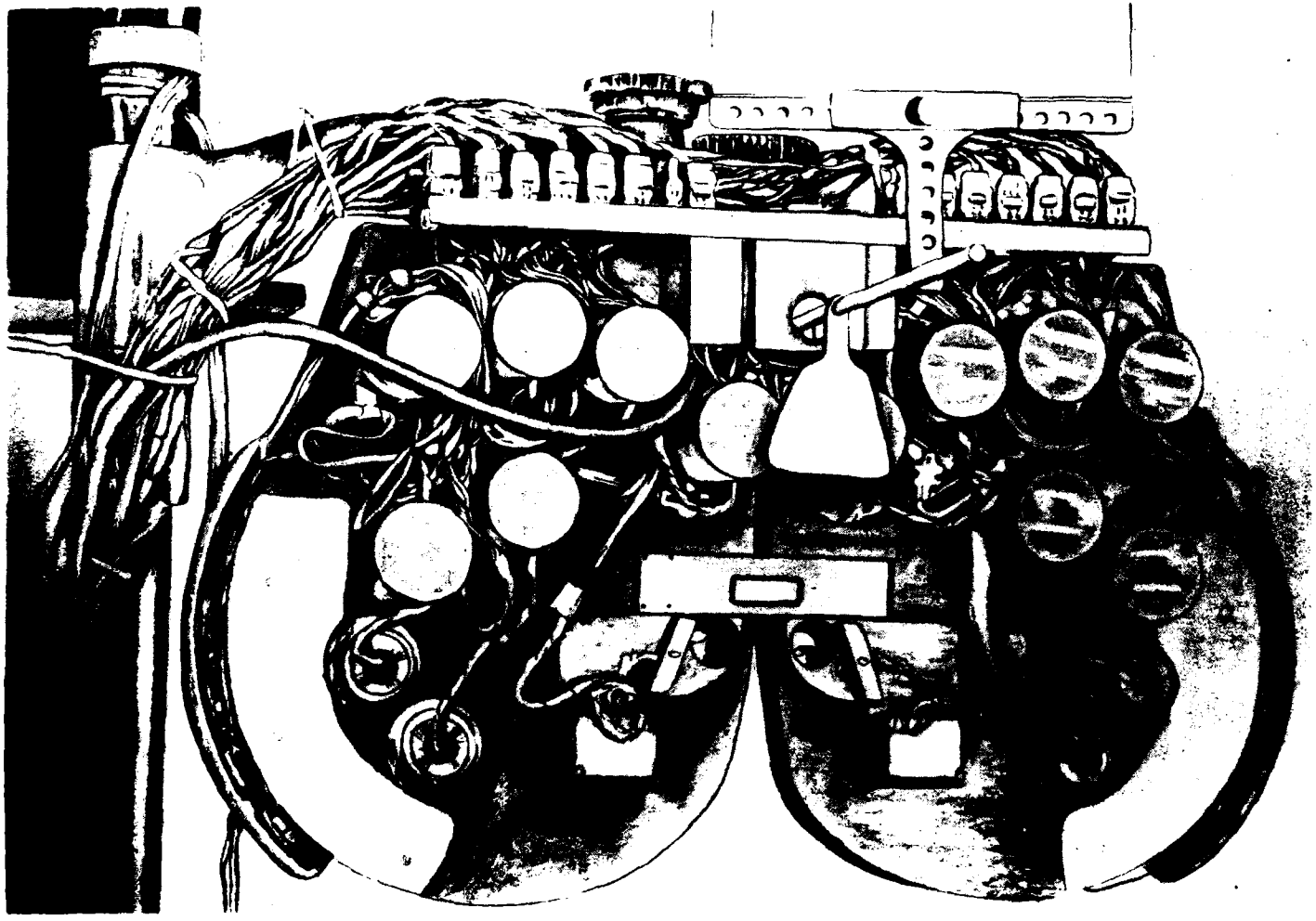

PLATE D Refractor III

Chapter 6
COMPUTER-ASSISTED SUBJECTIVE REFRACTION WITH COMPUTER-ACTUATED REFRACTOR III

Principles of Flow Charts and Trials

IN SUBJECTIVE eye examination, a series of rules and a battery of tests are used to determine the refractive state of the eye. Experienced clinicians have an intuitive feeling for these tests and how they are used, and usually find it very difficult to analyze what they are doing step by step. It is difficult to extract or recall all the subtle rules, especially the implicit ones, used in applying these tests to a patient. No matter how well one thinks a flow chart for a particular test has been designed, experience often proves there are subtleties not yet considered that must be included to make the test useful. These oversights are readily correctable as a rule, with the help of insights gained from patient responses.

In contrast to oversights, there is another class of fault or error which is more fundamental to computerized eye examination. Automated systems in their present form allow for only limited system-patient interaction. This is a departure from the usual subjective examination that omits some of the basis for its success. As an example, the clinician does not usually take the patient's word for his refractive error by asking if the letters are clear or blurred, but has the patient read the line in order to give a test that is directly assessable by the clinician himself. A computer system that cannot do this kind of checking is subject to increased errors; however, these errors can be minimized by frequent visual-acuity checks during the examination.

The flow charts consist of a dozen or more subroutines which provide the individual tests making up the subjective examination. They also include the audio recorder messages and the symbols used throughout. Not all the flow charts that have been devised are operational. Some have been revised and others completely rejected and discarded, having been found wanting in clinical trials. Some, though included in the list, are not yet implemented. The tests, or subroutines, have to be put in some sort of sequence, and this sequence itself is the subject of a flow chart. Visual acuity must be measured, and it is also charted.

The human clinician has information from the patient's old prescription and old spectacles, if any, and also from retinoscopy. These sources of information provide for him what we have called *objective results*, and these have been put into a flow chart, to provide the same information for the computer. If no objective results are available, the computer must start *de novo*. In this case it uses an approximate sphere test in order to find what the approximate spherical error is. The computer then makes the usual comparisons of spherical lenses (as in the situation where the clinician asks "which is better, lens number 1 or lens number 2?") and these comparisons are written up in a *sequential spherical test** flow chart. Before the computer does the radial line or

*This term was devised to distinguish it from the *simultaneous spherical test*, which was tried and found wanting. It used spherical lenses, +0.25 DS on the right half and −0.25 DS on the left. Two identical charts were displayed, one in the right field and the other in the left. The patient could simply move his eye from the one to the other to change the power and make a virtually simultaneous comparison. In practice the sequential spherical test was found to be more accurate (even if not as rapid), apparently because of alignment difficulties in the simultaneous method.

grating test for astigmatism, it is necessary to place convex lenses before the eyes in order to blur the target somewhat, bringing the astigmatic interval of Sturm forward into the vitreous humor of the eye. This is called the fogging technique, and a flow chart entitled *check degree of fog* is designed to do that. Next, the cylindrical axis is determined by gratings of different orientations, and this procedure is also in a flow chart. After the cylindrical axis is determined by the grating test, the approximate cylindrical axis is sought by the crossed-cylinder test. Next, cylindrical power, using the cross (or, in classic parlance, the *crossed*) cylinder is determined and the axis is remeasured for a refined value. Refractor III is capable of providing a bichrome spherical test and a binocular balance test among others, but these tests have not yet been implemented in the programming. The *astigmatic test interaction* program evaluates the axis values obtained from the grating astigmatic test and approximate cross cylinder axis test to determine the initial axis value for the final cross cylinder axis test. The *effectivity program* allows a correction for the effectivity errors that affect all refractors but are not corrected in any of the conventional ones used today. Finally, a test for the presbyopic condition takes the positive and negative relative accommodations, determines an add, and also determines the near visual acuity. These flow charts will now be discussed in some detail.

Tape Recorder Messages

The Refractor III system has a cartridge recorder with four stereophonic or eight single channels. It provides long messages on an endless loop. An integrated circuit with appropriate solid-state memory operating by continuous delta modulation provides the short messages. The short messages, such as "Number one" and "Number two," are of good telephone quality and require 16.5K bits per second. The longer messages, which will be changed to solid state when the necessary memory becomes available or the technology is improved, give instructions for visual acuity, sequential spherical correction, and the various other tests for which the patient must have instructions in order to respond. Some of the messages, such as those of encouragement, approbation, and greeting, have not yet been implemented in the programs.

Experience has taught us that in asking for a choice, such as between two lenses, assigning the top and bottom buttons of the answer box to these alternatives avoids the confusion some people have in distinguishing right from left. We have found no one who confuses top and bottom yet, although it might well occur in one who has a tenuous grasp of the English language. The right button is reserved for equality, and the center button is the same throughout all the tests except for the astigmatic grating test, where it is used to indicate equality. In acuity testing, each of the four buttons surrounding the central one corresponds to the possible position of the opening in the Landolt broken ring or C.

Symbols

Computers require symbols as abbreviations for economy of memory. Wherever possible, the symbols used in computer-assisted eye examination are those traditionally used by the optometrist, such as OD for right eye, OS for left eye, and OU for both eyes. New symbols have been devised that are abbreviations not normally needed in eye examinations, such as LC for letter chart, NA for no astigmatism, NS for near screen, ORX for old Rx, and VAAE for visual acuity with empirical add. Some symbols are peculiar to the computer aspects of the program, such as symbols for counters and reaction time. The assignment of symbols to various new concepts was designed to be as mnemonic as possible.

Testing Sequence

One of the first questions arises over what sequence the program should have. For example, if there are objective results, such as an old Rx or retinoscopy, how should they be used in expediting the current examination? As shown in the testing-sequence flow chart, after the unaided or naked visual acuity is taken for each eye, the computer asks whether objective results are available. If they are, visual acuity is recorded with each set. The computer chooses the best objective result giving visual acuity above 20/50 as the starting point for the sequential sphere test. If no objective results are available, or if none gives an acuity better than 20/50, the

program goes on to the approximate sphere determination first, which would start the refraction essentially *de novo*. The sequential sphere test is used next in either case to check the spherical correction. If the objective results include a cylindrical lens, then the axis is checked with the cross cylinder and subsequently the power is also checked with the cross cylinder, which then leads to the sequential spherical test to recheck the correctness of the spherical correction. However, if there is no objective cylinder then the grating astigmatic line test is used to find an axis. If no axis is found, the program goes on to the sequential sphere. However, if an axis is found here, then the power and refined cross cylinder axis are determined before one goes on to the sequential sphere. The final result for distance vision is the *suggested Rx* and the visual acuity for each eye is taken through it. If the patient is over 39, near tests are performed. If not, the subjective examination is completed.

Visual Acuity

There are two sequences to taking visual acuity, as shown in the visual-acuity tree. The first is the *jump* sequence, which is the determination of acuity over a large range by a rough scale and yields the general level for a finer determination. The finer determination is the *step* sequence, which brackets between adjacent lines in order to determine the clinically exact acuity more precisely. In the jump sequence, the Landolt broken ring or C for 20/400 is presented. Assume the patient chooses the correct opening two times in succession and the program now moves the slide projector to present a 20/100 target. If the patient now responds incorrectly, the program enters the step sequence at 20/200. In entering the step sequence, let us say the patient responds correctly twice in a row, and the program then presents the 20/100 letter. One incorrect answer brings back the 20/200 letter, and two correct answers again brings it down to the 20/100 level. Another incorrect answer fixes it at 20/200. Since the probability of guessing a correct answer for each Landolt ring is 25%, the combined probabilities for 6 correct answers come out to a 0.1% chance of this being an erroneous answer; that is, one which arrived at this endpoint by guesswork rather than by being valid.*

When calling the visual-acuity subroutine for the jump sequence, the first question is, roughly what is the level of visual acuity? Should the jump or the step sequence be called, and with a ring of what size? If the acuity is equal to 20/400 then obviously the jump sequence must be followed, but if it is equal to 20/50 then the step sequence would be better, called at the value of the best visual acuity. Entering the jump sequence at 20/400, assume that the patient makes two incorrect answers and is continued on the 20/400 Landolt broken ring. A counter keeps track so that after two additional unsuccessful attempts the visual acuity is recorded as less than 20/400 and the routine ends. However, if the 20/400 ring is mastered, then there are two possibilities. If there have been errors on the 20/400 ring, then the counter would indicate it and the patient would enter the step routine at 20/200 because he is somewhat uncertain at the 20/400 level. However, if he has had no such difficulty, he continues with the jump routine at the 20/100 level. If he fails this he enters the step at the 20/100 level. If he does not fail, the jump continues down to the 20/50 level. Here, failure would raise his level at the jump routine to 20/70, but success would bring him down to the 20/30 level. From this jump level a step level is entered either at a higher or lower acuity, depending on the answers of the patient. Correct or incorrect answers change the step to the next one below or above, as the case may be. Six correct responses at the threshold-acuity level determine the endpoint of the visual-acuity test. The results are written into the patient's file and the subroutine is ended.

Objective Results

In this subroutine, the computer asks whether an old Rx is available, and if it is, measures that acuity and compares the visual acuity with it relative to the best visual acuity found thus far;

*This probability would be modified if the patient knew that the program never shows the same slide twice in a row. If it did, the lack of a slide change would make it obvious that it was the same slide being projected. The carousel slide capacity is not large enough to have duplicate slides with the same orientations for this purpose, but the problem does not seem important.

PLATE I Automated testing of VSAM data

that is, without any lenses. If the acuity is better, it is flagged in the patient's file. Then the next question is asked, is retinoscopy available? and similarly, the computer takes the visual acuity through it. If the acuity is better than the best acuity thus far, the former value is flagged in the patient's file, and the program goes on to ask whether any other objective results are available, and if they are, repeats the same acuity-measurement procedure. Ultimately the program goes on to ask itself whether the best visual acuity is better than 20/50, and if it is the sequential sphere subroutine is called next, with the best objective Rx as the starting point. If it is not, then the approximate sphere subroutine is called. That is the end of the subroutine.

Approximate Sphere

As mentioned earlier, this routine is employed only when there are no useful objective results, that is, with an acuity $\leq$ 20/50. In principle, objective results should always be available. Even if there is no old prescription, one can at least perform retinoscopy; it is working under a handicap to start without this basic information. It is not reasonable to pit the computer system without this piece of data against a human refractionist who has the advantage of objective results, for example retinoscopy. However, the computer as well as a human clinician can overcome this handicap if necessary.

In this flow chart the power factor (PF) is introduced, which is a means of using different size of steps in the choice of various lenses when larger ones are too gross or finer steps would take too long, or be less easily discriminable. Initially PF is set anywhere from two to eight, depending on whether the visual acuity is good, where small steps can be distinguished; or poor, where they cannot. If the acuity is 20/20 or better, then a comparison is made between plano and +1 D. In this and subsequent flow charts one often sees a diamond with a limitation of +24.50 DS or −26 DS. These limits recognize the spherical power range of Refractor III and prevent error from an endless loop occurring if the powers called should exceed those available. In that unlikely instance, a diagnostic or error message is issued on the teletypewriter. If number 1 or the plano lens is chosen, then the approximate Rx is made equal to the temporary sphere preferred by the patient, ending the subroutine.

Going back to the beginning, we now assume that the visual acuity was 20/400 or worse. Now the power factor is 8, which makes the temporary sphere equal to −0.50 D times the power factor, or −4 D. Thus number one is −4 D and number two is +4 D. If the patient prefers number one, that is, −4 D, then the temporary spherical correction is set at plano as number one, and −4 D as choice number 2. If number 1 is selected, then the flow chart leads us to change the power factor to half of what it was, that is to four, and then sets the temporary spherical correction to +1.50 D times four, which is +6 D. Now the patient is given a choice between number one, +2 D, and number two, which is −2 D. When the patient has gone through the loops an adequate number of times, dividing the power factor by two so that it ultimately becomes one, the preferred sphere is set as the approximate spherical power to end the routine.

Sequential Spherical Correction

This is the traditional subjective test for spherical correction where two choices are offered the patient, often labeled number one and number two. The line chart is entered, the various counters are initialized, and the power factor is set to two. The temporary spherical power is set as the approximate spherical power and now the patient is asked which lens makes the letters clearer—number one, which is the temporary spherical power, or number two, which is +0.50 D more based on +0.25 D multiplied by the power factor of 2. If the convex lens is preferred after one has gone through various changes and counters, the sequence is repeated with more convex power. However, if earlier the concave lens section had been traversed, then counter D would be set at one, which would indicate a bracketing reversal had occurred, and the power factor would then be reduced to 1. If this were the first time the plus pathway was traversed, the flow path would go back to try more plus power until a second reversal occurred (G = 2), the sequential spherical correction would be set as found, and the subroutine would end.

Trying a different path, assume now that the patient prefers the more negative, or less convex, lens; that is, number one. After we go through various counters, the temporary spherical correction would be changed by -0.50 D times the power factor of two or -1.00 D. If the traversing of this pathway occurs after the patient had been through the convex-lens pathway as originally described, then counter Z would be set to one and the power factor would be reduced to one, to provide finer steps for the final determination. In this way the spherical correction is determined much as the clinician does it, using large steps at first and refining the test to small steps towards the end.

Check Degree of Fog

Fogging is used as preparation for the grating or radial-line astigmatic test. In order for astigmatic lines or gratings to provide correct information about astigmatism, accommodation must be suppressed and the interval of Sturm (between the two foci of astigmatism in the eye) brought anteriorly into the vitreous chamber by adding enough plus to drop acuity to 20/40.

Cylindrical Axis, Astigmatic Line

The axis is determined by means of a series of lines or gratings in the form of three or four disks presented simultaneously with different orientations. This procedure was devised so that the patient could choose various axis preferences without the need for more than four slides. Another limitation was to five possible responses, so that the simple response box could be used. If radial lines with a clock dial were to be used, six responses would be necessary, which is beyond the limit of the response box. Although twenty-nine different grating slides are in the carousel and available, only four need be used in any trial to determine the axis within 4–5°. The first slide presented shows a grating with an axis of 135° on the left, 45° on the right, 90° or vertical at the top, and 180° or horizontal at the bottom. If all gratings appear equally dark and sharp, then the center button is to be pressed, which in this first slide would indicate that there is no astigmatism. (This is the only routine in which the center button is not used for a repeat of the instructions.) Assume that the bottom button is depressed to indicate that the patient has chosen the 180°, or horizontal, lines as the best. The computer chooses the next slide number, number 5. This slide presents three gratings, one at the top (180°, the previous choice) and one each on the left and right to bracket 180° by +22½° (157½° and 22½°). The patient now has the opportunity to bracket in the 180° region. Let us assume that he presses the top button, or 180° grating again. The computer now turns to slide number 9, which brackets 180° more closely (±11°). If the patient now presses the top button corresponding to 11°, the computer switches to slide 29, which offers the patient a choice of gratings 5½° apart along with lines at 5½°, 11°, and 180°. The grating chosen in this case becomes the cylindrical axis or astigmatic line choice.

If the patient originally had pressed the center button on the first slide which displayed gratings at the four cardinal directions, then one slide would have sufficed to indicate that there was no astigmatism.

Approximate Cylindrical Axis, Cross Cylinder

After the letter chart is entered and everything is initialized (including the counters), the patient is asked which lens makes the letters clearer. Number 1 is a -0.25 DC at a given axis with the cross cylinder placed with one axis coincident. For number 2 the cross cylinder is shifted 90°. If number 1 is chosen, the procedure is repeated; if number 1 is chosen the second time then the approximate axis is set at the temporary axis and that is the end of the routine. However, if number 2 is chosen, the axis is shifted 45° and the test is tried again. Each time number 2 is chosen the axis is shifted another 45° until there have been five trials. After five trials without a choice it is assumed there is no axis and the approximate axis is set to none. However, if at any one of these axes there does appear to be an effect then the number 1 route is taken and that sets the axis. The notation keeps the axis, which is shifting by 45° increments, between 0° and 180°, in accordance with the usual clinical notation: a horizontal axis is 180° (and not 0°) and axes are never designated as higher in value than 180°.

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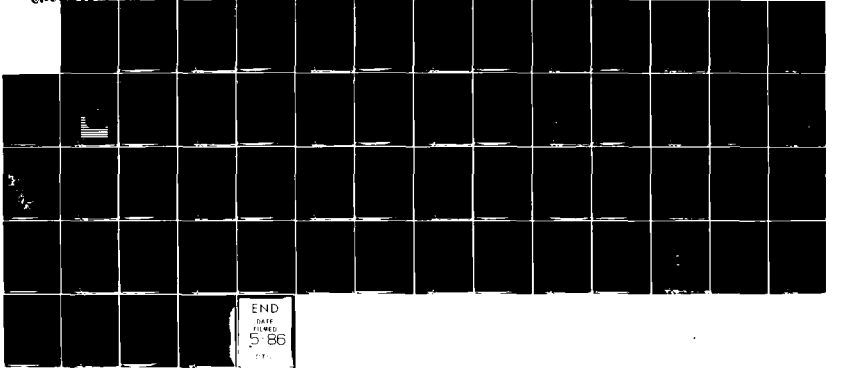

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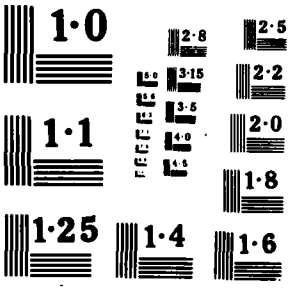
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Cylindrical Power, Cross Cylinder

After the usual initialization and message, the first crossed cylinder axis is set to the temporary axis; the temporary cylinder power, –0.25 DC, times the power factor is set at the temporary axis; and the temporary spherical power is set to the approximate spherical power, +0.12 D times the power factor. The patient is then asked whether this, number 1, is better, or whether number 2 is better. Number 2 includes the second cross cylinder, which is at right angles (90°) to the first crossed cylinder. If the patient decides number 1 is better, the flow threads its way through the various rectangles and diamonds back to the main starting rectangle, that is where the first cross cylinder is set at axis XT. But now the cylinder power is greater since the power factor has increased by one. The cylinder becomes –0.50 DC and the same procedure is followed. If the number 2 or equal buttons are pushed then counters K and Z are set to zero and one respectively, and, provided the power factor is zero, G is then raised to one and the left loop is repeated once to confirm that no cylinder power is preferred. If cylinder is found, the program exits from the right loop when the D counter is one, indicating a preference reversal at the approximate cylinder power, which is then set at –0.25 DC times the power factor. The approximate spherical correction is set to whatever it was +0.12 D times the power factor, which is the end of the subroutine.

Another pathway could have been traversed. The patient response could have been to repeat the same choice of lenses, in which case if K were not equal to 2, K would be raised by 1, presumably from zero to 1, and the lens choice repeated. However, if this pathway were traversed twice, then K would be equal to 2 and various decision diamonds would be traversed to reduce the cylinder power and offer another choice of lenses.

Perhaps an explanation should be given of the counters. For example, in the lower right side of the flow chart there is a diamond that asks whether D = 1. This feature, combined with the flow in the *no* direction where D = D + 1, shows that D is used to indicate whether this diamond has been traversed before. The mechanism is seen at the lower left side, where the question is whether G = 1. A negative response raises G to one so that the decision diamond indicates the next time that the path has been traversed. When the decision diamond asks whether Z = 1, it has a slightly different purpose. Here it is determining that Z, if it is equal to one, has been on the other side of this flow chart where Z has been set to one from its initialization value of zero. This feature provides for convergence of the response by bracketing from one side to the other.

Final Cylindrical Axis, Cross Cylinder

After the initialization, including the setting of counters, long message number 6 is played and provides the instructions. A decision diamond has already been traversed to avoid playing for the left eye when it has already played for the right eye. Cross cylinder number 1 is set at 45° from the temporary axis. If that should turn out to be an axis of 0° or less it is corrected by the addition of 180° to it. Lens number 2 is the second cross cylinder, which is shifted 90° in axis from the first crossed cylinder. The two cross cylinder lenses are used in place of the usual manual flipping of a single one. If the patient chooses number 1 then the flow goes past various counters to rotate the temporary axis by –M/4, which is –10°. Again an adjustment is made if the axis goes out of the conventional range of 1 to 180°. The program then returns to the cross cylinder choice. If number 1 is chosen again, the cylinder is rotated by another –10°. This procedure can continue until the counter G is reduced from 6 to 0, which would indicate an error in the axis, since there is an axis shift with no reversal through 60° and an error message is printed out.

Let us now assume that the patient responds initially by choosing lens number 2 as being better. He now goes up to six increments, rotating the axis in increments of +10°. Again, the seventh time indicates an error in the axis.

Assume now there is a reversal. The patient has been through lens number 1 being better and now he reports that lens number 2 is better. In the first instance counter D has been set to 1. Since D = 1, the path sets M equal to half of what it was, resets G to 6, and D to 0. The

axis is now rotated back 5°. We now retrace our steps and assume that for the next choice number 2 is better. Z is now set to 1 so that M is now set at half of what it was, which is now 10, and therefore the axis is rotated in 2½° increments. This seesawing can continue until the equal button is pushed twice in succession, at which time the approximate axis is set as the temporary axis and the subroutine is over. The test may also end when the M counter is 5, that is, just after the axis of the cylinder is rotated by the smallest increment, 2½°. An artist's version of the flow chart is seen in Plate F.

Astigmatic Test Interaction

The astigmatic test interaction compares the axis obtained by the astigmatic-line subroutine with that of the approximate-axis cross cylinder subroutine and determines how they will be integrated in the final recommended prescription. If there is a temporary axis from the astigmatic line routine, it is set as the first approximate axis. If there is not, the axis is set arbitrarily to 180°. These settings provide a basis for the start of the approximate cross cylinder axis in which the astigmatic axis test is made every 45° over a total range of 180°. If the cross cylinder determines an axis in this test, it is set as the second approximate axis; if not, a flag is used to show there is no axis. There are now four possibilities. The astigmatic line could have (1) shown an axis or (2) not, and the cross cylinder test could have (3) shown an axis or (4) not. The goal now is to set the approximate axis on the basis of the first or second approximate axes, as determined in the astigmatic line or cross cylinder tests. If the cross cylinder test shows an approximate axis and the astigmatic line shows none, then the approximate axis is simply set to

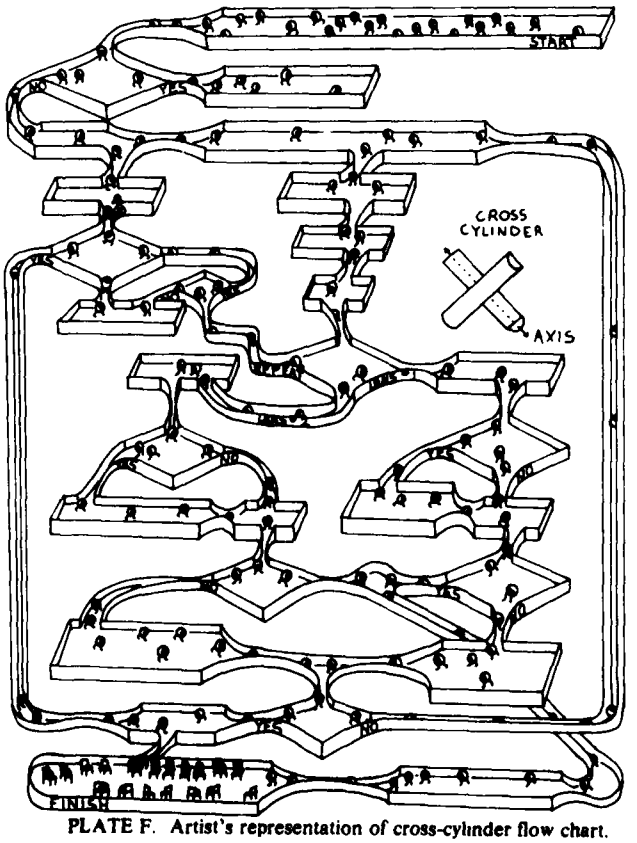

PLATE F. Artist's representation of cross-cylinder flow chart.

the second one which issued from the cross cylinder test. If the cross cylinder test shows no axis and the astigmatic line shows no axis, then the routine goes on to the sequential sphere test. If both tests show an axis and these axes are the same, this value is set as the temporary axis and the routine goes on to the cylindrical-power cross cylinder test. However, if they are not the same, then the temporary axis is set to the cross cylinder axis, the latter being taken as the more reliable value, before going on to the cross cylinder power test. If there is no cross cylinder axis but there is an astigmatic line axis, it becomes the temporary axis.

After the cylindrical power test, if there is no cylinder power, the program goes on to the sequential sphere routine; but if there is a power, the final axis is set by the final-axis cross cylinder test. If the final-axis cross cylinder test produces an axis shift of more than 15°, then the cylindrical power and final axis tests are repeated.

Near Add

After initialization with the near screen down (i.e., in position for use) and the near projector switched on, the near visual acuity is measured. Next the empirical add is obtained from the memory of the computer in accordance with the age of the subject and the temporary add is set at the value of the empirical add. At the same time the power factor is set at two. Long message Number 7 is played, which asks the patient to push the top button when the letters are clear, and the bottom button when the letters are blurred. If the letters are clear, the temporary add is increased by +0.25 D times the power factor, which in this case would be +0.50 D; the procedure is repeated until blurring occurs. At that time, it would be expected that the temporary add would be larger than the empirical add; since they are not equal, the path passes through the diamond at the *no* position. The next decision asks whether the power factor is equal to –1, which it is not. Passing through the *no* position, the next diamond asks whether the power factor is equal to 2, which it is, and it exits at the *yes* position, setting the power factor to 1, and reducing the temporary add by –0.25 D. Again, the patient is asked whether the letters are clear or blurred. If they are now clear again, plus a quarter is added; if they are blurred, the flow comes down through the diamonds and sets the negative relative accommodation at the difference between the temporary and empirical adds. The power factor is now set to –2 and the presentation of lenses now comes in –0.50 D increments. On the next transverse through the vertical series of diamonds, the power factor of –2 is reset to –1, which represents a change of +0.25 D. The exit is through the diamond where the power factor = –1 and that sets the positive relative accommodation at the temporary add minus the empirical add. With the negative and positive relative accommodations in the memory, the computer now can set the final add as equal to the empirical add plus the average of the sum of the positive and negative relative accommodations. The near visual acuity is now taken with the final add and that is the end of the subroutine. An additional diamond asks whether the final add is greater than zero. This check insures that no negative or zero add is offered through some error.

The principle of this test is first to provide the negative relative accommodation by changes in the lens increments in +0.50 D steps, backing off in 0.25 D steps until it is clear, at which time the value is taken as the negative relative accommodation. Then the power factor is set to –2 and the positive relative accommodation is advanced in 0.50 D steps until the chart is blurred. At the occurrence of blur the power factor is then set to –1 and the prescription backs off in +0.25 D steps until it is clear again. When it is clear, +0.25 D is added and then the blur takes it through the –1 power factor decision to set the positive relative accommodation and adjust the addition.

Evaluations

Three groups of patient volunteers were examined at the Letterman Army Medical Center (Marg et al. 1977, 1978a, 1978b). Included were active-duty personnel, retired personnel, dependents, and a miscellaneous group including civil-service personnel and students. They were examined by optometrists using standard refraction procedures (which is termed manual) as well as by the system.

In the first evaluation, tests were performed on 78 patients. These were the first systematic clinical trials after the best efforts at the drawing boards were completed (Marg et al. 1977). Eighty-three percent of the distance prescriptions generated by the system at this time were judged to be satisfactory.

For about half the patients the prescription for present glasses or retinoscopy was entered into the computer file before testing. The computer used these "objective results" to increase the speed and reduce the initial uncertainty of the procedure, as does the human clinician. When the computer system is not provided with objective results it is operating under a relative handicap, but a special subroutine called "approximate sphere" is automatically called to try and compensate for this lack of information.

The order in which patients were examined manually versus the computer system was mixed. It was primarily governed by administrative convenience. This order did not seem to be of any importance.

The results were compared and evaluated (Marg et al. 1977). Three categories were used, the first two of which comprised the Satisfactory group.

1. good agreement: little doubt that the system prescription would be satisfactory;

2. agreement: enough difference to believe that either the system's or the human clinician's findings or both may be in slight error, but the results would probably be acceptable to the patient; and

3. unsatisfactory: the system is in error.

The Agreement category may be difficult for some clinicians to accept because some believe that there is only one satisfactory value for each eye within a quarter of a diopter. If they could watch students function in an optometry clinic they would observe that the students find values according to the well-known biases of the instructor who will check and grade them. Some instructors expect (and their students find) maximum acuity; others may expect more convex lens, perhaps +0.75, in the same patient, as long as the acuity does not fall below 20/20. Patients of all these instructors seem, by and large, satisfied regardless of the bias. Our Agreement category reflects this latitude, which should not be considered an error.

In the case of Unsatisfactory, it is important to subcategorize the type of problem. For example, if it is a hardware or software problem, these "bugs" can be remedied and avoided in the future. If the problem is in the optometric concepts designed in the flow charts and not a limitation of the method, this too can be remedied by reformulation. However, if the patient becomes confused and cannot follow instructions or if the patient does not want to accept the computer system, the remedy is neither apparent nor easy, and for these patients the basic concept may be at fault. This error is fundamental, in contrast to the readily correctable ones mentioned above.

Results

The lens prescriptions obtained by the computer are tabulated in Table 6–1. Of the 78 patients, we judged that approximately 83% could be provided with a satisfactory or useful

TABLE 6–1. Evaluation of computer-assisted refractive error in determinations based on comparison with conventional clinical methods.

	Initial Trials		Debugging Trials		Final Trials	
	Number	%	Number	%	Number	%
Satisfactory	65	83.4	70	87.5	76	95.0
Good agreement	(57)	(73.1)	(59)	(72.8)	(67)	(83.75)
Agreement	(8)	(10.3)	(11)	(13.6)	(9)	(11.25)
Unsatisfactory	13	16.6	10	12.5	4	5.0
Avoidable system error	(5)	(6.4)	(5)	(6.5)	(1)	(1.25)
Fundamental patient error	(3)	(3.8)	(3)	(3.6)	(2)	(2.5)
Error of unknown cause	(5)	(6.4)	(2)	(2.4)	(1)	(1.25)
Totals	78	100.0	80	100.0	80	100.0

prescription from the computer system. Seventeen percent could not. Of the latter, about 6% were avoidable by improved hardware, software, and flowcharts. Another 6% failed for undetermined causes. About 4% failed because of a mental or physical inability or lack of desire to accept or to respond to the instructions. There appeared to be nothing that could be done to avoid errors by those confused by the simple instructions, short of prolonged training or education sessions. On the basis of the initial tests we concluded that about 90% of the patients may receive a satisfactory prescription once the obvious instrument failures are corrected. If the undetermined causes of errors are correctable, it is possible that as many as 96% of the patients may receive a satisfactory prescription. Four percent of the patients did not seem to be able to cope with an automated system but needed human intelligence and understanding.

The sample of near corrections shown in Table 6–2 is much smaller because of the smaller number of presbyopes, and because of the cases in which an unsatisfactory distance prescription rendered the lens add inapplicable. Of 28 patients, 68% received a "useful" add, and 32% did not. The avoidable errors for the near add were large (29%) because of "bugs" in the programming and flow chart, all of which were later corrected. It became clear early in the trials that the near-add flow chart had these faults.

TABLE 6–2. Evaluation of computer-assisted determination of lens addition for *near* based on comparison with conventional clinical methods.

	Initial Trials		Debugging Trials		Final Trials	
	Number	%	Number	%	Number	%
Satisfactory	19	67.9	29	80.6	28	100.0
Good agreement	(18)	(64.3)	(24)	(66.7)	(24)	(85.7)
Agreement	(1)	(3.6)	(5)	(13.9)	(4)	(14.3)
Unsatisfactory	9	32.1	7	19.4	0	0.0
Avoidable system error	(8)		(7)	(19.4)	(0)	(0.0)
Fundamental patient error	(1)		(0)	(0.0)	(0)	(0.0)
Error of unknown cause	(0)		(0)	(0.0)	(0)	(0.0)
Totals	28	100.0	36	100.0	28	100.0

Discussion

The most difficult part of the evaluation we performed was deciding whether a given difference in prescriptions was clinically significant, i.e., whether one prescription would be satisfactory and the other not. Determining which of two prescriptions would be more satisfactory was easier because such a judgment is relative rather than absolute. Visual acuity helped us in this relative judgment. Also of value to us was the plus-bias rule that states that for the same acuity, more convex lens is preferred.

A valid method for determining differences that are difficult to categorize would be to provide the patient with two pairs of glasses, one with the clinician's result and one with the computer's. The patient would not know the source of each prescription. After a suitable interval, the patient would report whether one is preferable to the other, or if they are both equal. Furthermore, when there is a preference, the patient should be asked whether the less preferred prescription is adequate. Such a method was not employed in this initial evaluation for reasons of economy and the rules for the protection of human subjects.

Two future courses of action were clearly indicated. First, the system had to be improved mechanically, electronically, and in the optometric flow charts. Our goal was to obtain virtually no unsatisfactory results caused by avoidable errors. Second, an effort had to be made to determine the thus-far unknown causes of errors. Were they really avoidable errors, or were they fundamental errors? Third, those patients whom we categorized as making fundamental errors had to be reconsidered to determine whether these errors could be overcome. For example, if the error were due to poor hearing, perhaps special earphones or other aids for the partially deaf could be used. If the error stemmed from confusion in pushing the buttons, a separate training machine might be useful. The patient would use it to practice before the regular examination, until a simple test was passed.

The second clinical trial with 80 patient volunteers (Marg et al. 1978a) was specifically designed to identify the errors in the hardware, software, and optometric flow charts. Improving the obvious errors seen in the initial trials brought the satisfactory results for the distance prescription up to 87.5%. The discovered sources of error were varied. Some were found in the optometric flow charts; some in the Fortran and assembly language routines at various operational levels.

The major problem was discovered in the operation of the pushbutton answer or response box. The error occurred when the patient pressed a button and held it down too long. The button was still registering when the next slide was presented and the previous answer registered in error. Installing an "initial edge detector" in each pushbutton circuit made any delay in the release of the button of no consequence.

It was also found that a "warm-up" or exercise program would prevent the errors that occurred when the occluders stuck. Another mechanical problem was obvious in the cartridge tape deck which announced lens "Number One," and lens "Number Two." These messages are played so often during an examination that the metal sensors on the tape tended to break down frequently simply from wear. By replacement of the tape unit with a Harris Semiconductor Corp chip which employs continuous delta modulation for voice encoding, moving parts were eliminated and reliability greatly improved. This device requires about 16½K bits/sec memory and gives speech of good telephone quality.

Many other changes were made but most were accomplished too late to affect the level of satisfactory results for these trials. It was estimated that once all the currently uncovered errors were corrected it should be possible to approach a 95% satisfactory operation.

The final evaluation with 80 patient-volunteers was performed after all possible corrections had been finished (Marg et al. 1978b). It showed 95% satisfactory results for distance and 100% for near. Not all the errors were completely eliminated at the beginning. For example, there was at times a recurrence of a "hunting" oscillation of the cylinder axis, which was called axis chatter. This fault sometimes slowed the test but did not directly affect the results.

An upgrading of the hardware and further improvement of the software and optometric flow charts can make the system even better. Use of the system in its planned mode of assisting the clinician rather than pitting it against the clinician as was necessary in these trials should also give better results. The following developments are in progress.

1. *Binocular testing.* All the hardware exists for performing various binocular tests including heterophoria, prism duction, etc. The development of flow charts and their translation into algorithms will make automated binocular tests a reality.

2. *Microprocessor interface.* Currently the system interface consists of hardwired logic circuits. Since it was designed, the development of microprocessors has made the logic circuit obsolescent. The same job can be done by microprocessors with greater economy of cost, size, and weight, and proven greater flexibility and better control.

3. *Retro-illuminated display chart.* By a modern microprocessor-controlled adaptation of the old back-lighted eye chart, popular half a century ago, the display will have no moving parts and higher reliability.

4. *Floppy or flexible disks.* Replacement of the dual digital magnetic tapes with floppy disks would decrease memory access time and thus the examination time.

5. *Refractor III.* The refractor has proved to be generally rugged and reliable. It can be improved by the redesign of certain aspects:

a. better occluders (so that a warm-up is not required)
b. lower friction in bearing surfaces, to allow smaller stepping motors and faster movement
c. replacement of the mechanical rim encoders by photoelectric ones
d. reduction in weight and size
e. redesign with an eye to less expensive production
f. improved appearance by covers that conceal wires and cables

Computer Measurement of Visual Acuity

The determination of visual acuity is central to any eye examination. An acuity measurement is used to evaluate both the initial performance of the eyes and the results obtained through any prescribed correction.

For our purpose, there is no need to go into the fine, esoteric points of what is visual acuity and the various ways in which it may be measured. Our model of visual acuity determination is that done by a clinician in a regular eye examination. This kind of measurement is relatively rapid and sufficiently accurate to grade patients according to their useful degree of acuity. From a practical viewpoint, visual acuity, as it is currently determined clinically, is entirely satisfactory. Its greatest potential weakness lies, not with the method, but with the skill and conscientiousness of the examiner. He may not wish to take the time and effort to produce highly accurate results. It may be adequate to produce results that are satisfactory but not necessarily the most precise. The use of Snellen optotypes has become almost universal in countries that have a high literacy rate and use Roman or similar letters, but equally good results can be obtained with other characters, such as Landolt broken rings or C's, and illiterate E's. In 1965, when we first considered computer-assisted eye examination, it became quickly evident that the solution to automated eye examination depended on the successful automatic registration of visual acuity. By the term *automatic* we do not mean *objective*, because visual acuity is normally a subjective measurement. Until recently, objective acuity measurements were of questionable validity.

Some years ago, von Bekesy (1947) devised a new audiometer in which the subject, in effect, took his own thresholds. It used the method of "up-and-down" of Dixon and Mood (1948) which was originally devised for the testing of explosives. (See also Dixon and Massey 1957.) Called the "staircase method," it was applied by Cornsweet (1962) to psychophysical measurements but had not yet been applied to the determination of visual acuity. The staircase method is extremely efficient and requires presentation of many fewer stimuli than any other psychophysical method. Once the first few stimuli are out of the way, all the other stimuli are very near the threshold level so that each one contributes importantly to the final computer threshold value.

Marg, Liberman, and Crossman (1969) used the staircase method for the determination of visual acuity in a manner simulating computer testing. Since no computer was yet available to them, the experimenters changed the letter sizes manually in the same fashion as the computer would and demonstrated that the automatic determination of acuity was feasible. This experiment led to the actual computer determination of acuity in accordance with the same principles (Crossman, Goodeve, and Marg 1970). The determination of visual acuity by the automatic method was in agreement with the manual Snellen chart determinations. A reasonable compromise between the conflicting requirements of simplicity, speed, and precision was achieved.

The automatic method is best understood as a further development of the conventional manual procedure for determining visual acuity with a Snellen chart. The patient is asked to read a more or less random sequence of alphabet letters of a given size or visual angle subtense. The clinician notes the correctness of each response and judges whether or not the patient appears able to resolve that size of detail within a reasonable time. After this judgment the optometrist presents smaller letters if the response is correct, or larger letters if not, and the procedure continues, finishing when the clinician has found the smallest row or column of letters that the patient is able to read. The acuity is given in a fractional form as the distance (which is directly relatived to the subtense) of the just readable letters relative to that of the normal subject. It is expressed as 20/X, where X is the distance in feet at which the normal person can just read the smallest line that the patient can read at the 20-foot distance. Normal is 20/20 or detail of 1 minarc. If the patient fails to read one or two of the letters on a line, or succeeds in reading a few of the letters on the next smaller line, a notation may be appended to the fraction indicating slightly more or slightly less acuity than the fraction otherwise indicates. Some clinicians use simply plus and minus, others indicate the number of letters missed, such as 20/20–2. (In Europe 6/6 for 6

meters would be used in place of the metrologically archaic 20/20.)

The patient may think he is choosing one letter out of a set of 26 choices, but certain letters such as *I* and *W* are not normally used on Snellen charts, since they are too simple or too easily confounded. The correctness of the response is assessed by the clinician, who usually encourages guessing in order to avoid the common error of underestimating visual acuity. If the patient guesses, he will be correct by chance once in 26 times, which is a probability of 0.038. By inverse probability, a single correct response permits a strong inference that the subject can actually read the letter, since the likelihood is only 3.8% that he was unable to read it and yet made a correct guess. With two consecutive correct responses, the probability equals about 0.038^2 or 0.0016, so that the likelihood of error is reduced to 0.16%. This computation ignores differences in the discriminability of letters, which is beyond our concern here. A single error thus permits 96.2% confidence that the well-motivated patient cannot read the line in question. Reading letters is thus a fast and accurate method of determining the visual acuity.

The basic difference between the manual examination and the computer examination is one of communication. The computer can present all the letters of the alphabet, but the patient would need a teletypewriter keyboard to respond, which would be too complicated for him. On the other hand, the computer could present an illiterate E or the Landolt broken ring or C in one of four directions and the patient would need only four keys to respond, one for each direction. If the four-choice Landolt C target is used, the probability of a guess being correct is 0.25 and five successive responses (which yield a probability of 0.001) are required to reach the same certainty about the target the patient can actually resolve as that obtained from two correct alphabet letters. A single correct response yields only 75% confidence of believability, and two successive ones are required for 93.8% confidence. Therefore, a four-choice procedure may be expected, other things being equal, to require about 2½ times as many responses to reach a similar confidence level as a 26-choice alphabet.

The original program was run on a PDP-8/I with 4K 12-bit words of core memory, and a 1.5-microsecond memory access time. This program actuated a random-access carrousel slide projector containing 80 slides, with an access time of about 1 second. The program employed approximately 500 machine instructions. Computations were performed in binary arithmetic and the results were punched on paper tape and/or printed on a teletypewriter. Subsequent analysis of the data was performed on the same machine by means of a Fortran system.

Fourteen student subjects were used, some of whom were selected for poor uncorrected acuity. This group, with a mean age of 21 years, of good intelligence, and apparently free from disease, was certainly not a random sample from the total population of potential patients, but it was not unrepresentative. None of the subjects was experienced in computer usage, eye examination, or psychophysics. None of them experienced difficulty in performing the required task, and all gave satisfactory results. For these early trials a four-position joy-stick was used in place of pushbuttons, but later in our work we found the pushbuttons to be simpler and easier to use. Visual acuity comparisons were made on an American Optical Co. Snellen chart (No. 194) at 20 feet, with about 10 foot-candles of illumination.

Figure 6–1 shows the results from one subject. Two conditions were used, in the experiment, A and B. Condition A required guessing if the subject could not discriminate. It was a forced four-choice experiment. In condition B an additional "don't know' ' button was provided, and the subject was asked not to guess. These two conditions actually gave the same results and the forced four-choice method alone was retained.

Although the basic concept of automatically recording visual acuity was shown to be valid and practicable, it was desirable to speed up the procedure. For this reason the subsequent programs were divided into two categories: (1) the jump procedure, which would be a coarse change of acuity-chart stimulus size, and (2) the step procedure, which would be a fine change. Jump sequence would start with the 20/400 character or ring and quickly proceed to the region of the threshold. Then the step sequence would take over, and in small steps determine the actual threshold. This procedure saved time.

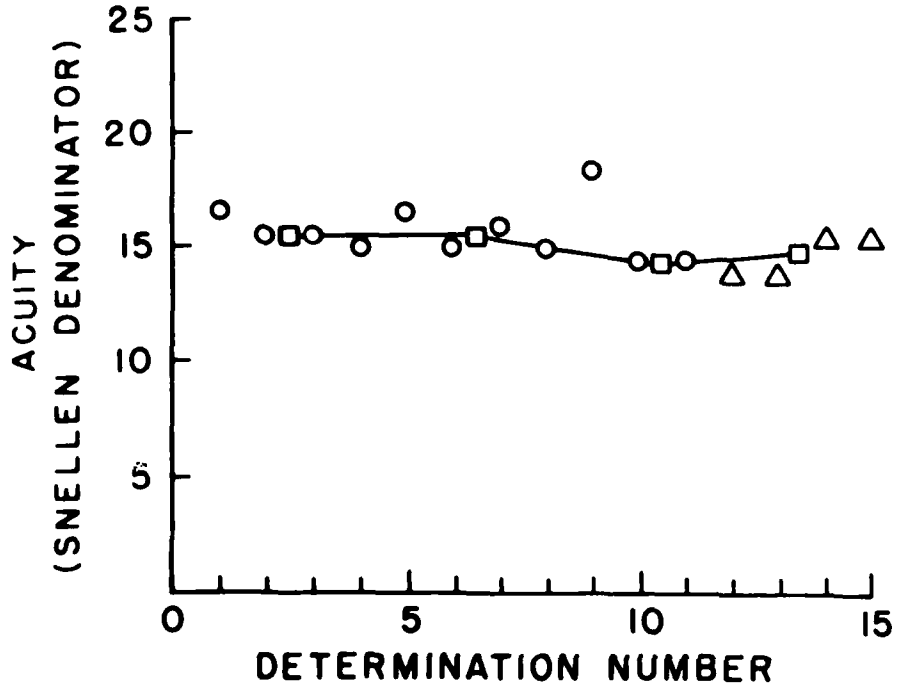

FIG. 8.1. Sequence of automated visual acuity determinations from one subject. Circles indicate positive response options only and required guessing if subject could not discriminate. Triangles represent data obtained with an additional "don't know" button when the subject was asked not to guess. Squares represent both conditions. (Crossman, Goodeve, and Marg, 1970.)

Our basic computer-based method of determining acuity has been adopted by Decker et al. (1975). They constructed a small machine for this purpose. Various other automatic methods of determining acuity such as that of Millodot and Harper (1969) have not to date proved clinically practicable. One method that is very promising and has been used on human infants is the visual evoked potential (Marg et al. 1976). However, this method would be cumbersome relative to the computer-based method described earlier unless one were already recording evoked potentials for some additional reason.

Computer-actuated Refractor III

The design and construction of Refractor III (Plate D) came as a result of the experiences gained from the design and construction of Refractors I and II. They have been treated in some detail elsewhere (Marg 1973).

Refractors I and II were based on a trinary system. Refractor I was activated by solenoids, whereas in Refractor II pneumatic motors were used, triggered by relays, which controlled air orifices. Refractor I was not well designed mechanically, which prompted the change in design in Refractor II to a pneumatic system.

The trinary optical system was adopted for two reasons. First, a trinary system is easily translatable to the binary system on which the computer is based. Second, but more important, a trinary system provides for a given step size and range a minimum number of lenses. It provides not only an economy of lenses, which may be trivial in the overall cost, but there are also fewer lenses, which may simplify effectivity error corrections.

A series of both positive and negative lenses is employed: ±0.25 D, ±0.75 D, ±2.25 D, and ±6.75 D. These lenses, in pairs on a vane, can be combined in such a way as to give a range of ±10 D in quarter-diopter steps. Positive and negative lenses of the same power are never required simultaneously.

A similar approach is used for cylindrical lenses. Only negative or only positive cylinders are required. Customarily, in optometry negative cylinders are used. The lens pairs become -0.25 DC on one side of a vane and -0.50 DC on the other side. The next vane would be -0.75 DC and -1.50 DC, and the next would be -2.25 DC and -4.50 DC. This series would give a maximum range of -6.50 DC. Of course cylindrical-test lenses must be rotatable to provide the desired orientation of the axis.

As indicated earlier, Refractor I was built on the trinary model, in which linear solenoids to displace each vane to either side of the center were used. The inertia and friction of the vanes holding the lenses was too great for the small, short-stroke solenoids. Their power was marginal and was inadequate to overcome any imbalance. In the original design the vanes were to be moved by flexible cables from the remote solenoids. However, the friction in these cables forced us back to the drawing boards. There, a direct-lever, push-rod linkage to the solenoids was designed and built. Spring tensions were so critical in their adjustment that it soon became evident that Refractor I had a faulty design and might find its greatest utility in a museum.

Refractor II, based on the same trinary system, did work well mechanically. However, it became apparent that a pneumatic motor system had not as high a reliability as would an electro-mechanical system in which stepping motors were used. Moreover, despite its economy of lenses because of its trinary concept it lacked the range of powers and variety of auxiliary lenses needed in a practical system. Also, Refractor II required a source of compressed air, which meant a bulky, noisy, and heavy air compressor. For these reasons Refractor III was designed and built. Refractor II did fill a function in teaching us how to design and test flow charts during the considerable period that Refractor III was under design and construction.

Refractor III was designed around four lens-holding disks. Disk 1, on the ocular side, contained the high spherical lens powers (to minimize effectivity error corrections). Disk 2 contained the low spherical powers. Disk 3 had the high-power cylindrical lenses; disk 4, the low-power cylinders as well as prisms. In addition, auxiliary devices were included such as a stenopaic slit in disk 3 and cross cylinders in disk 4. Disks 3 and 4 were designed to allow a rotation of the orientation or axis of the lenses. Each disk had 25 round ports holding 24 lenses or other optical devices. One port was left empty. Occlusion was accomplished by special electromagnetically controlled occluders on the front of the instrument.

Disks 3 and 4 are each controlled by two stepping motors and are therefore independent of each other, not only in relation to position but also to axis orientation. Thus, if desired, the prism from disk 4 can be used at a different axis from the cylinders on disk 3. Smaller disks with 8 to 16 apertures would have required more disks in the design for the same steps and range of power and would have complicated the effectivity errors and reduced the field of view. A disk with fifty or more lenses was conceivable and desirable in that it would reduce the number of expensive stepping motors. However, the large size would be awkward and would take twice the time for the "worst case" change of lenses, through 24 ports rather than 12.

All positions are fed back to the computer so that the computer can alert an operator if its commands are not successfully executed. The cylindrical or prism axis, that is the axis orientation of disks 3 and 4, are fed back by shaft encoders. The positions of each disk are encoded by special rim encoders. The vertical positioning of each lens is critical, especially in the high powers, because of undesirable prism effects when the lens is not exactly centered. On the higher powers the lens centers must be aligned well within a millimeter. This problem has been solved by a special photoelectric detector, which insures accurate positioning.

The headrest incorporates proximity detectors so that the computer can react in any preprogrammed way to the patient being out of proper position in relation to the spectacle plane of the instrument.

A translucent near screen activated by a motor controlled by the computer is automatically put in place for the near tests. The screen itself is of translucent material and retroilluminated by the near slide projector.

In place of a manual "flip" cross cylinder, two cross cylinders in adjacent ports on the same disk are used, 90° apart in orientation. Thus it is a simple matter to rotate disk 4 from one to the other to give the flip effect. Another possibility would be simply to rotate one cross cylinder by 90° very rapidly, but that part of the system cannot respond fast enough to obtain the flip effect.

Little has been said about binocular testing. It is generally agreed among optometrists that binocular tests are important and desirable. There is some room for argument about the number and kind of tests that should be included in a basic eye refractive examination. The fundamental reason that no binocular tests have been included thus far in our system is simply a matter of priority. It has been necessary to get the monocular tests functioning well, since they are fundamental and basic to the examination. The binocular tests have been postponed until the monocular tests are better developed.

There is no basic limitation in computer examination technology as to the type of binocular tests that can be devised. Binocular test flow charts have been devised (see Appendix I) but they have not yet been translated into algorithms. All the necessary optical devices such as prisms and special lenses are available. All prisms can be oriented vertically, horizontally, or anywhere in between. Separate controlled rotation of the prisms before the two eyes is possible, and in this way finer gradations than the step increments available can be worked out if desirable. A minor limitation exists in that the prisms reduce the number of gradations possible in the cylindrical lenses since the prisms and some of the cylindrical lenses are in the same disk for each eye.

A different approach has been used by Larson (1971-1973; Larson and Outerbridge 1974). Larson applied stepping motors to rotary prisms in order to perform various prism tests. Rotary (Risley) prisms were considered for Refractor III but it was decided that single prisms in the disks gave an adequate choice of prism vergence powers without the additional stepping motors and optical surfaces for the eye to look through. A system such as Larson's might make an excellent orthoptic instrument and be quite cost effective when controlled by microcomputers.

The Alvarez-Humphrey variable spherocylinder lens was also considered for our application. Its primary disadvantage is that it has a limited range. A practical refractor should have as a minimum spherical powers of ±15 D. With the Alvarez-Humphrey lenses available at the time, auxiliary lenses were required to extend the range. In our application there seemed to be little disadvantage as long as auxiliary lenses would be needed, since the simplicity of the linear control of lens power (with a stepper motor driving rack and pinion) would be complicated by the auxiliary lens system.

Safir and Kashdan (1976) have built an ophthalmic computer-based databank system. The data from an ophthalmic examination are entered into the computer memory by means of a light pen on the cathode-ray oscilloscope face. Values are announced vocally by an enunciator to assist a technician who is performing the examination without an understanding of the strategy. It tells the technician through a branching program what to do next. The technician enters the data into the system, which controls the next instruction. This method, when implemented, will be similar to our system except that it will obviate the need for a computer-actuated refractor, along with the response box and computer-controlled display. The obvious disadvantage of this approach is that it requires a human being doing something that a computer can do. Nevertheless a person of less training and skill can be used than with no computer at all.

Refractor III is a useful clinical instrument with a greater range and accuracy than any other refractor. Figure 6-2 shows the printout from an actual examination taken by a volunteer patient at Letterman Army Medical Center during system evaluations.

The final judgment on systems like Refractor III and its successors will be made primarily on economic grounds (Plate G). It appears to be cost effective provided the instruments are kept well utilized, as they would be in a properly organized large clinic (Bohman, 1977).

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NAME:                                   IDENTIFICATION NO.:          5628
ADDRESS:                                REFERED BY: DR RUTLEDGE
PHONE:                                  LAST EYE EXAM: 1977
PATIENT'S SEX: F                        PLACE OF LAST EYE EXAM: LAMC
PATIENT'S AGE: 40                       DATE OF R3 EXAM: 27-JUN-77 14:26:50
OCCUPATION:                             DATE OF PRINTOUT: 20-APR-78 13:52:42

OD                                      OS
VA    SPH     CYL     AX  TIME  VA    SPH     CYL     AX  TIME

VA W/O RX:
400   PLANO                   0:57  400   PLANO                   0:33

VA   <OLD RX>
20    -2.75   -0.50   67  0:58  20    -2.75   -0.75   91  0:55

SEQUENTIAL SPHERICAL CORRECTION:
      -2.75   -0.50   67  1:45        -2.75   -0.75   91  1:04

FINAL X-CYL AXIS:
      -2.75   -0.50   64  1:56        -2.75   -0.75   35  0:53

CYLINDRICAL POWER:
      -2.37   -0.25   64  1:24        -2.37   -0.50   35  0:42

FINAL SPHERICAL CORRECTION:
      -2.37   -0.25   64  1:19        -2.37   -0.50   35  1:10

FINAL CORRECTION:
25    -2.12   -0.25   64  1:43  20    -2.37   -0.50   35  2:02

SUGGESTED RX:
20    -2.75   -0.50   67  0:00  20    -2.37   -0.50   35  0:00

NEAR TESTS:

VAAE AE      TIME       NRA     VAAF AF      TIME     PRA       VAA0 TIME
     +0.25               +1.25   25   +1.37   0:28     +1.00     25   0:52

EFFECTIVE RX:
+?3   -2.62   -0.50   67  0:13        -2.37   -0.50   35  0:00

  TOTAL TIME FOR ENTIRE COMPUTER AIDED RX: 13:54
```

FIG. 6–2 Computer printout of the results from an examination by Refractor III.

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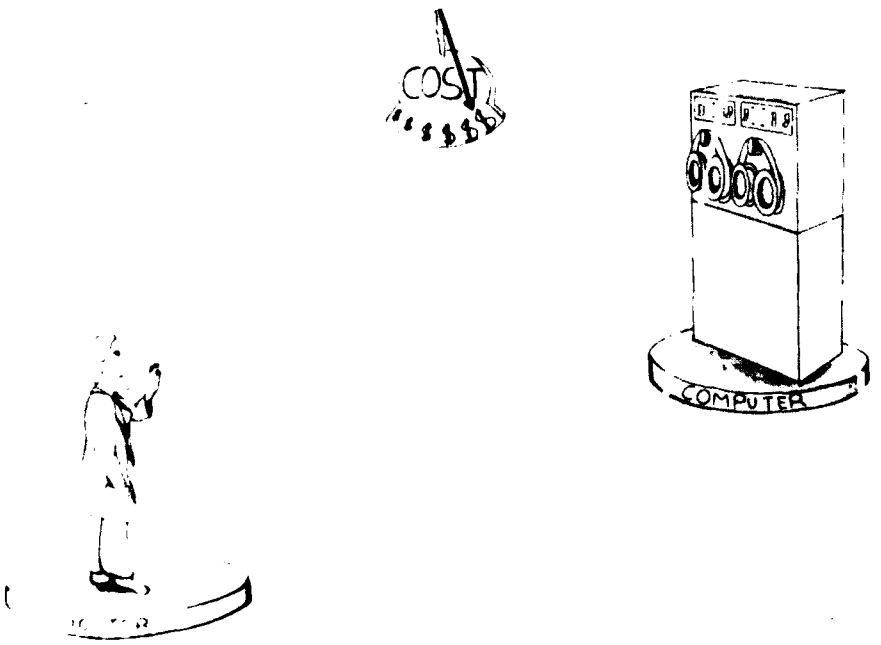

PLATE G. On an economic scale, people cost more than computers.

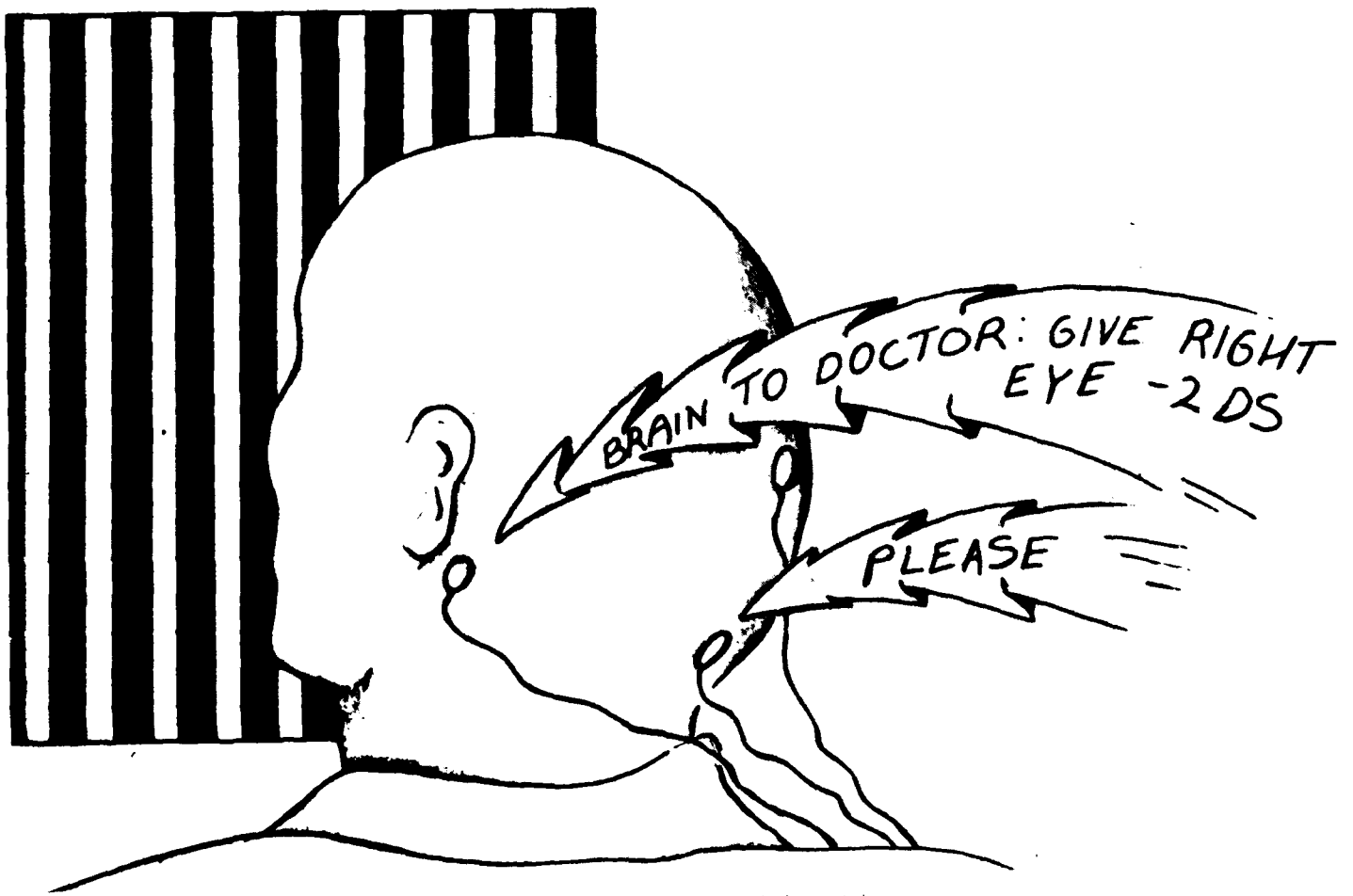

PLATE II Refraction by visual evoked potentials

Chapter 7
COMPUTERIZED OBJECTIVE REFRACTION AND VISUAL EVOKED POTENTIAL

AN OBJECTIVE measurement of the refractive state of the eye is highly desirable but in most instances not essential. Most clinicians routinely take an objective measurement by retinoscopy (also known as skiascopy) and use it as a guide to the subjective refraction. In those uncommon instances in which a subjective refraction gives equivocal results, or perhaps cannot be done because one cannot communicate with the patient, the objective refraction may be used as a substitute. However, as the subjective refraction uses the best visual acuity as its endpoint, it provides the most useful value for the correction of refractive error and the prescription of glasses.

There have been several theories as to why retinoscopy does not give an ideal refractive-state measurement. One possibility is that the reflecting surface for the skiascope shadow seen in the plane of the pupil is not that of the end organs of the foveal photoreceptors but is based instead on some other reflecting layer. Another theory is that much weight is given to parafoveal and peripheral areas of the fundus, which have a different refractive measurement from that of the fovea. In any case, the refractive state of the foveal cones is for the most part not being measured and it is the sharpness of the imagery at these end organs that provides good, central visual acuity.

For almost a half century several objective eye refraction devices have been on the market, sometimes called *refractionometers* (Chaps. 2 and 3). These instruments work in much the same way as large ophthalmoscopes on instrument stands and measure the refractive state when the fundus is brought into focus. They are objective in terms of the patient, but not, of course, of the examiner, who must make a judgment as to clear focus. Refractionometry is not as difficult as retinoscopy, nor does it take the long training for competency. Refractionometers have never become popular because they are much more expensive and cumbersome, and the results are no more accurate than those of a retinoscope in skilled hands. Refractionometers have been proposed for use by government agencies in times of disaster when skilled clinicians may not be available in adequate numbers. However, they do not provide a prescription that is any better than that by any other objective means.

As discussed in Chap. 2 and 3, in the past few years three *automatic retinoscopes* which are completely objective have become available. The first is Safir's Ophthalmetron, manufactured by Bausch & Lomb. The second is the Visual Acuity 6600 originally designed by Cornsweet and Crane, manufactured by Acuity Systems, Inc. The third is made by Coherent Radiation, Inc. and is called the Dioptron. These instruments all cost from $15 000 to 30 000 and give no more information than that obtained with a skillfully used retinoscope. They have not become widely popular, although they have been used to provide objective examinations administered by relatively unskilled assistants. For this reason they have been of economic value in some practices. They cannot be generally used as a substitute for the subjective examination as some originally assumed (Pappas, Anderson, and Briese 1978a, 1978b).

Visual Evoked Potentials

Visual evoked potentials are potentials that can be obtained from the visual system, generated by visual stimuli. Ordinarily these potentials can be obtained from the eye by a contact-lens electrode, or from the brain by electrodes on the scalp. In order to distinguish between evoked potentials from the retina and those from the brain, the latter are called *visual evoked cortical potentials.* However, most investigators make this distinction by using the classical name *electroretinogram* for a potential from the eye and simply *evoked potential* or visual evoked potential for that from the brain. The term *visual evoked response* (VER) is identical with *visual evoked potential* (VEP).

The active electrode for evoked potentials is usually placed over the occipital area in the midline, 2 cm above the inion, the protuberance at the back of the head. Changes in visual stimuli generate potential changes largely in the visual cortex which are picked up by the active electrode.

The visual evoked response recorded from the scalp, which may be about 5 μV, is generally much smaller in amplitude than the electroencephalogram (EEG, about 50 μV). In the present context the EEG is considered noise, and therefore averaging is required to be able to distinguish the evoked potential from this along with other background interference. The signal-to-noise ratio is improved by the number of samples N, averaged by $N/\sqrt{N}$. Averaging computers are available for around $5000 but a basic system complete with visual pattern stimulator currently costs up to $20 000 (Table 7–1). However, a computer is already available in combination with a computer-assisted eye examination facility. Only an averaging program is needed, along with suitable analog-to-digital and digital-to-analog converters and amplifiers.

The literature on visual evoked potentials is large and growing. For a general background the reader is referred to the most definitive current textbooks in the field, by Regan (1972) and Desmedt (1977).

The use of averaging to extract small bioelectric signals from noisy backgrounds originated with Dawson (1954). Visual evoked potential recording blossomed with the commercial availability of averaging computers in the early 1960s. At first most experiments were performed with homogeneous flashes of light free of stimulus contours or patterns. A number of investigators attempted to number or name the separate waves of the evoked potential just as the electroretinogram was characterized by *a*, *b*, *c*, and *d* waves half a century earlier. Each investigator published a different VEP waveform (Fig. 7–1). Although these diverse results can be attributed in part to a lack of standard light stimuli and electrode placement, there are also large individual differences and variations in response to homogeneous or unpatterned light stimulation. It was not until the early 1970s that it became generally recognized that form stimulation is preferable to flash stimulation, testing more precisely the capabilities of the visual system. Spehlmann (1965) first showed the importance of using form stimulation, comparing checkerboard stimuli with blank or unpatterned light flashes. He also showed a decrease in the amplitude of the evoked potential to a checkerboard stimulus when the patterned target was blurred with a +10 D lens.

Reitveld et al. (1967) demonstrated that the patterned evoked potential was primarily, if not entirely, a response of the central visual field (Fig. 7–2). As the pattern is removed from an increasing central area, the response diminishes. When the stimulus pattern is removed from the central 4°, little or no response is seen because the fine checkerboard stimulus can be resolved only by the central, most acute part of the visual field; the more peripheral retina cannot resolve the pattern and thus does not contribute to the response. Furthermore, the central macular area is far more extensively represented in the visual cortex than the peripheral parts of the visual field. The authors also used a subtraction method, taking the responses to an unpatterned stimulus from those of a patterned stimulus to provide a pure patterned response, a manipulation that assumes linearity.

At about the same time the beginning of a series of brilliant analyses of the evoked potential appeared by Spekreijse (1966). His results (Fig. 7–3) also show the central-field character of the patterned evoked potential with the diameter at about 3°. (This phenomenon provides a

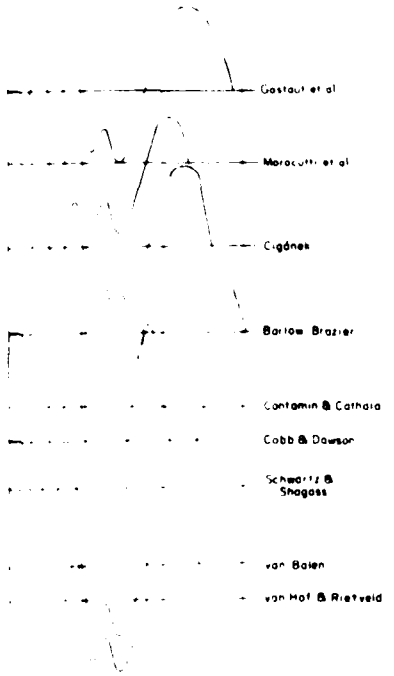

FIG. 7-1. Comparison of visual evoked potential obtained by various investigators. Waveforms differ because of lack of standardization of stimulus and electrode organization and placement. More repeatable waveforms are generated with patterned stimuli than with homogeneous, nonpatterned light flashes as used here. (From Gastaut and Régis 1965.)

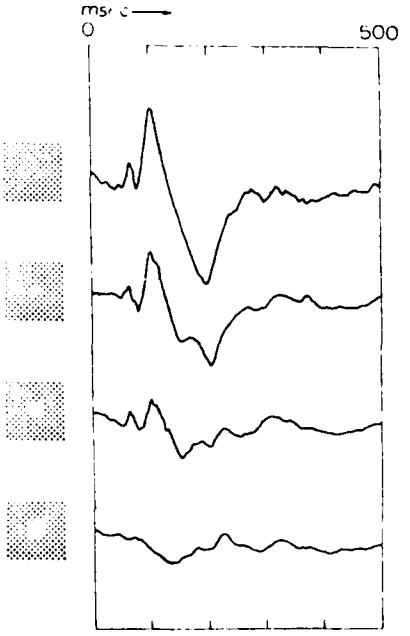

FIG. 7-2. Contribution of central foveal area to pattern response. Stimulus is checkerboard approximately 12° square with increasingly larger central area blanked out. Curve at top is from complete checkerboard stimulus. Second from top has 2° diameter central area blanked out. Third and fourth curves are 3° and 4°, respectively. Response curve is generated primarily if not entirely within central 3°. (From Reitveld et al. 1967.)

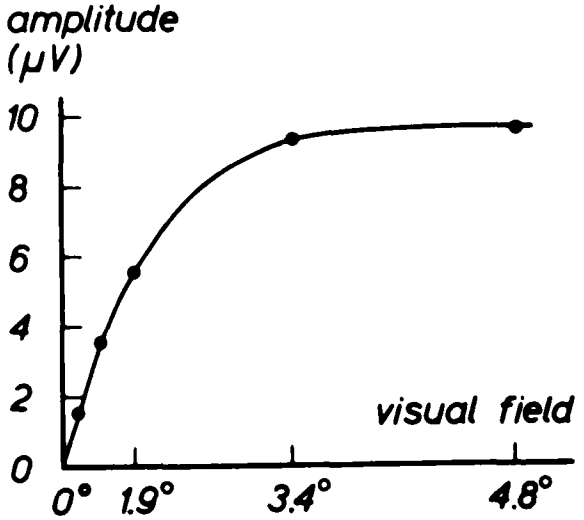

FIG. 7-3. This curve supports conclusion from Fig. 7-2 that effective area for pattern response of visual evoked potential is approximately the central 3°. (From Spekreijse 1966.) Two eyes, counterphase; chessboard pattern, 10'; 4.9 cps, 15% mod., 3000 asb.

TABLE 7-1. Commercial visual evoked response systems.

Manufacturer	Model	Channels	Display	Visual stimulus	Cost ($), 1977	Remarks
Grass Instrument Co. Quincy, MA 02169	10 ERS with Visual Pattern Generator, VPG-1	2—1024 words each (4 channels available)	Cathode-ray oscilloscope and X-Y recorder	12-in. black-and-white TV. Step control of checks and bars, spatial frequency, repetition rate but not contrast. No provisions for mixing TV picture	10 ERS-2 $13 500 VPG-1 $1500 Complete $15 000	Highly experienced EEG manufacturer with excellent reputation for electro-physiological equipment. Has a research orientation. Microprocessor based
Nicolet Instrument Corp. 5225 Verona Road Madison, WI 53771	Averager CA-1000 Visual Stimulus NIC-1006	1024—20 bit words total for 1 or 2 channels	Built-in cathode-ray oscilloscope; X-Y recorder	CRO includes 13-in. black-and white and four colors. TV picture possible, but not simultaneously	CA-1000 $14 000 NIC-1006 $3000 Complete $17 000	Aggressive, relatively new company. More clinically orientated. Hardwired logic.
	Averager NIC-527	2048—20 bit words	CRT not included		NIC-527 $4500	
Princeton Applied Research Corp. Box 2565 Princeton, NJ 08540	TDH-9 Preamp. Model 113	1, analog. 400 bins		Not furnished	TDH-9 $4495 Preamp Model 113 $1075	High-quality state-of-the-art electronic instruments manufacturer. Low cost averager and expensive preamplifier, but not a complete system
Life-Tech Instruments Inc. Box 36221 Houston, TX 77036	Averager 7401 Recorder 7101 Strobe BF-2	1, with another available at higher cost 256 bins	Built-in strip chart recorder	Only strobe flash available	7401 $2500 7101 $4300 Complete $6800	Small, relatively new company. Low-cost equipment primarily for electroretinography and electro-oculography. Strobe flash is not adequate for pattern VEP studies.
Tracor Northern Scientific Co. 2551 West Beltline Highway Middleton, WI 53562	NS-570 Digital Signal Averager	1, with 2^{20} -1 word length, normally 1024 words	6.5-in cathode-ray oscilloscope and digital readout	Not furnished	$5450	Apparently designed and built primarily for physics and engineering rather than biomedical market. A new Clinical Analyzer TN-3000 is being announced.

TABLE [illegible] (Cont'd)

Manufacturer	Model	Channels	Display	Visual Stimulus	Cost ($)	Remarks
D. J. Faulkner 28 Falconhurst The Crescent Surbiton KT6 4BP England	Stimulator only			Visual stimulator television pattern generator for evoked potentials and psychophysical contrast sensitivity measurements	[illegible]500	Available on special order. To be manufactured by Medelec Ltd to replace other models listed below
Medelec Ltd Manor Way Old Woking, Surrey England GU2 9JU	Stimulator only			Visual stimulator television pattern generator for evoked potentials	1800	Most versatile stimulus when used with any size color TV. Can superimpose TV cartoon film to promote fixation in children
In USA TECA Corporation 220 Ferris Avenue White Plains, NY 10603	Stimulator only			Same as above for U.S. TV standards	4500	Same as above
FCEM Rue Louis Armand Z.I. Sud 77330 Ozoir-la-Ferriere, France	DITRAL 2048-MP	2048-16 bit words (8K RAM and 1K PROM)	Dual-beam cathode-ray oscilloscope	Not a CRT display. Can be reoriented for supine patient. 11 to 14 automatic programs. Set for N = 1 to 128	30000	Microprocessor based. Automatically tests each eye with red, blue, and white light. VEP, ERG, and EOG. Automatic testing of electrodes
Dagan Corp 2010 Minnehaha Ave Minneapolis, MN 55404	4300	One	Cathode-ray oscilloscope	Not furnished	4190	New entry in signal averaging. Based on 8-bit microprocessor
	4800	Four	Cathode-ray oscilloscope	Not furnished	5245	
San-Ei Instrument Co Medical Systems Corp 230 Middle Neck Rd Great Neck, NY 11021	7S11	Two	Cathode-ray oscilloscope *and strip recorder*	Not furnished	10000	Includes built-in acoustic stimulator for auditory evoked potentials
FDX Corp 2121 S. Susan Santa Ana, CA 92704	FDX-1000 AV P G 1	64K bits	Cathode-ray oscilloscope and strip (EKG) recorder	19-in. color TV	11 730	New company in field. Microprocessor based. Primarily for electrotromyography
Electronic Circuits & Systems 35 Glenside Rd South Orange, NJ 07079	OEU 4	One	Strip chart recorder	Slide projectors with electrically controlled shutters	8827	Capability claimed for ERG, EOG, and alpha rhythm

TABLE 7-2 Equivalent sizes in different methods of notation

Snellen	Minarc	Detail* (mm) (at 6 m)	Cycles per degree
20/15	0.75	0.22	40.0
20/20	1.00	0.29	30.0
20/25	1.25	0.36	24.0
20/30	1.50	0.44	20.0
20/40	2.00	0.58	15.0
20/50	2.50	0.73	12.0
20/80	4.00	1.16	7.5
20/100	5.00	1.45	6.0
20/200	10.00	2.91	3.0
20/300	15.00	4.36	2.0
20/400	20.00	5.82	1.5
20/600	30.00	8.73	1.0
20/800	40.00	11.64	0.75

*Multiply by 5 to obtain size of Snellen letters.

TABLE 7-3 Comparison of field size in cm to visual angle in degrees

	Linear (cm)	
Degrees of arc	One meter	Six meters
1	1.74	10.47
2	3.49	20.95
3	5.23	31.45
4	6.98	41.96
5	8.73	52.49
7	12.22	73.67
9	15.71	95.03
10	17.46	105.80
12	20.95	127.53
14	24.44	149.60
16	28.68	172.05
20	36.40	218.38
25	46.63	279.79
30	57.74	346.41

desirable feature for the clinical use of evoked potential measurements. Often fixation of the eyes may be uncertain because of lack of understanding or following of instructions, especially in infants and children, or a lack of ability to fixate, as in the amblyope or squinter. The stimulus screen can be of a 12° diameter or larger so that a fixation error from the center of the stimulus screen of 3° or more has little effect on the results.) Another point of interest in clinical application was the demonstration that checkerboard stimuli yield about double the evoked potential amplitude of gratings of the same size and detail. A larger signal-to-noise ratio requires fewer samples. Spekreijse also clarified the relation between saturation of the response and various stimulus parameters such as the degree of stimulus modulation (Fig. 7–4).

A systematic study of the effect of image blur was conducted by Harter and White (1968). They found that the refractive state of the eye might be determined from evoked potentials with the aid of trial lenses.

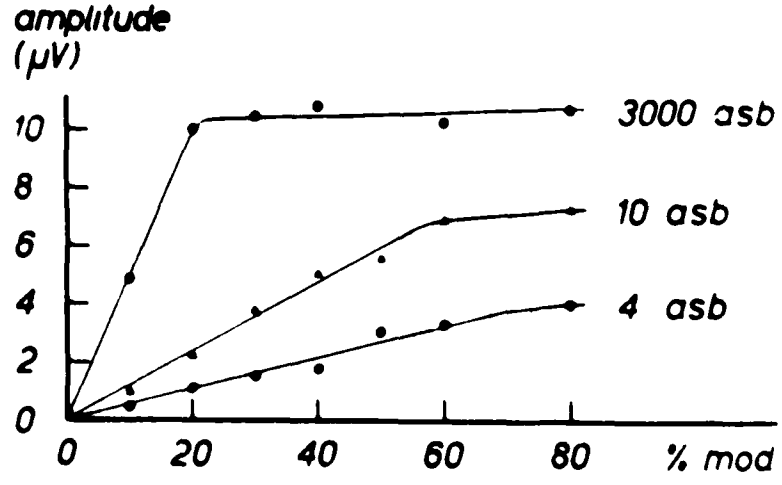

FIG. 7–4. Relationship between stimulus brightness, percentage of modulation, and response. Saturation occurs at relatively low percent modulation with bright stimulus, and with higher degree of modulation with dim stimulus. Abbreviation asb. stands for apostilbs, a European unit of luminance equal to $1/\pi$ candela per square meter or 0.1 millilambert. (From Spekreijse 1966.) Two eyes, counterphase; checkerboard pattern, 10′, 4.9 cps, 3.5°.

Principles of Visual Evoked Potential Refraction

Visual evoked potential amplitude, as indicated earlier, is a function of retinal image sharpness (Spehlmann 1965, Reitveld et al. 1967, Harter and White 1968). Evoked potential latency also depends on retinal image sharpness (Harter and White 1970, McCormack and Marg 1973). Hence, in principle, one need merely change the refractive state of the eye through various auxiliary lenses for a maximum amplitude response and/or minimum latency evoked response to determine the refractive state.

The determination of the sphere is relatively simple and straightforward. Harter and White in their systematic study employed translucent checkerboards which were briefly retroilluminated by a xenon flash source. They used about one flash per second and averaged approximately 100 response curve samples in order to obtain two points on a graph. These points gave the visual evoked potential amplitude at two separate defined latency ranges (90-100 msec and 180-200 msec) while the eye viewed the target through a spherical trial lens. Single stimuli flashed at intervals of a second or more can be characterized as the *transient* method. (Another transient method is one called *appearance-disappearance* by Spekreijse, but it is more than just transient since it also implies a constant average illumination. This method is now called *onset-offset* (Desmedt 1977) a term descriptive of the stimulus rather than the percept.) Figure 7-5 shows the response of two subjects who required sizable myopic corrections.

An alternative to the transient-stimulation method is the *continuous* or steady-state stimulus. Millodot and Riggs (1970) used a continuous sinusoidal oscillation, presenting a checkerboard with the checks in alternating antiphase at 7 Hz. The maximum amplitude of the sinusoidal visual evoked response was sought during the continuous pattern reversal with changes of spherical lenses. Figure 7-6 shows the response of one subject to the 7-Hz stimulus. Notice that 7 Hz is 14 alternations per/second, which is reflected in the sinusoidal response. Another way of considering the response is as a rectified sinusoidal wave which yields an apparent second harmonic frequency. Figure 7-7 shows the response of the evoked potential from the scalp and also of the electroretinogram from the retina to changes in lens power which varies retinal image

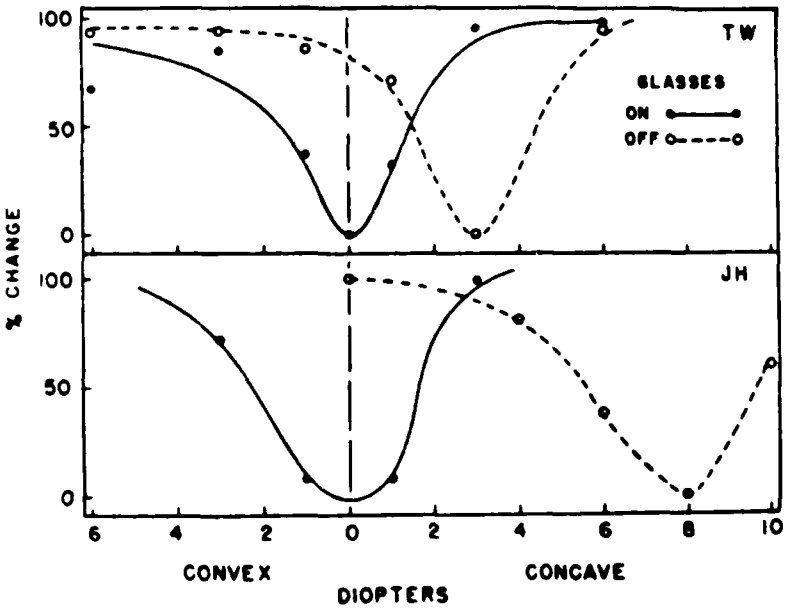

FIG. 7-5. Change in visual evoked response can be used to determine spherical refractive error. In upper graph subject shows refractive error of -2.5 D (myopia) with his glasses off. In lower curve subject shows change of -8.00 D without glasses. (From Harter and White 1968.)

sharpness. The sinusoidal output is a complex combination of the separate on and off responses a combination that can be analyzed for amplitude but not waveform because of its complexity

It is important to monitor the output of the amplifier before averaging to avoid noise which may be synchronized with the signal. Most troublesome in this regard is a strong output of alpha waves of the EEG (8-12 per sec). These waves can be driven or entrained by visual stimuli in their frequency range, so these frequencies are often avoided.

Using essentially the method of White (1969), and also Duffy and Rengstorff (1971) Ludlam and Meyer (1971) alternated the checkerboard stimulation with a diffuse, unpatterned light stimulation and electronically subtracted one from the other. The flashed checkerboard stimulates both the form and the light senses, whereas a diffuse flash of the same average luminance stimulates only the light sense. One can electronically subtract the latter from the former to try and obtain the response to form alone, assuming linearity of all the responses. Although this assumption may not be entirely valid (Spekreijse and van der Tweel 1972), still the responses seem somewhat better with this manipulation. The number of samples needed to obtain a useful evoked potential depends, of course, on the signal-to-noise ratio. The signal increases with N (the number of samples) and the noise decreases with $\sqrt{N}$, if we assume the noise is Gaussian. Thus, the more samples taken, the better the signal-to-noise ratio, but the more lengthy the

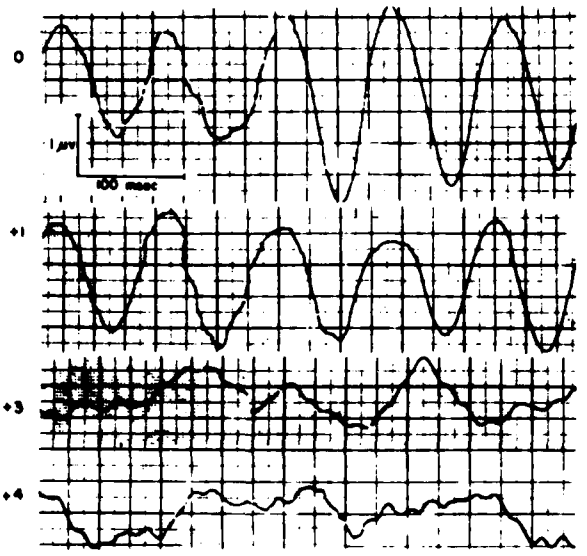

FIG. 7–6. Visual evoked responses to sinusoidal alternating checkerboard in antiphase at 7 Hz. Top curve is maximum response with the eye in focus. Subsequent responses with +1.00, +3.00, and +4.00 DS lens causing increasing blur shows parallel reduction in evoked-potential amplitude. (From Millodot and Riggs 1970.)

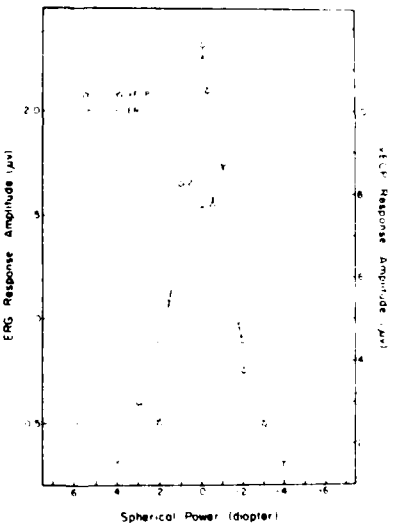

FIG. 7–7. Curves taken from data similar to those in Fig. 7–6 and from the same subject. The dashed line labeled *visual evoked cortical potential (VECP)* shows amplitude of evoked response from scalp. The solid line labeled *electroretinogram (ERG)* shows response taken from the corneal contact-lens electrode. Visual evoked potential is more peaked than electroretinogram, and therefore more sensitive and useful for determination of refractive state of the eye. (From Millodot and Riggs 1970.)

procedure, which is especially undesirable in clinical practice. In most visual evoked potential averaging a sample of 16 to 100 is adequate, depending on the signal and the noise.

A maximum VEP response is obtained from checks with 10 to 20 minutes of arc detail, and a contrast that does not oversaturate (Fig. 7-3, Spekreijse 1966). One scans with large spherical dioptric steps to find a rough maximum and then uses small dioptric steps to get the most precise result.

McCormack and Marg (1973) applied the principles of meridional refractometry to the visual evoked potential refraction. Gratings rather than checkerboard stimuli were used despite the smaller response in order to isolate the meridional value optically. There are three potential disadvantages to this method. First, it requires much mathematical manipulation to make the calculation, but that is no disadvantage if a computer is available as it would be in computer-assisted refraction. Second, the grating targets give about half the signal that checkerboard targets do, a deficiency for which we can compensate by taking more samples. Third, if the refractive state should vary, as it does when accommodation is active, large errors can result in the cylinder as well as the sphere. Placing the visual stimuli physically as well as optically 4 to 6 meters away helps minimize this effect.

With these electrical methods it is possible to obtain accuracies as good as 0.25 DS in spherical refraction with checkerboard stimulus. In meridional refraction the accuracy of the cylindrical lens may drop to 1.50 D, although results as good as half a diopter can be obtained at times. These techniques are as accurate as retinoscopy for spherical determination, but not as precise for the cylindrical values. Furthermore, the time required for these determinations is much longer than the few minutes retinoscopy generally requires. With future development, it is possible that the evoked potential method may become the best objective method and second only to subjective methods. Advances in techniques producing a higher signal-to-noise ratio by electronic and/or physiological means would serve this goal. At present, the only obvious way to achieve this goal is to place the electrode directly on the brain itself, which would make the procedure unacceptably invasive.

Fast Fourier Transform Refraction Analysis

Regan (1973) has offered a fast Fourier transform method of determining the refractive state of the eye in 2-3 minutes. A variable-power lens determines the average spherical refraction in seconds, the astigmatic value is then determined by means of a rotating stenopaic slit traversing 180° in about 20 seconds in a continuous meridional mode. The response from the scalp after amplification is fed to a quadrature circuit, which separates the x and y values and the phase. After some integration of the 7-Hz output wave, the response may be drawn on an x-y recorder, which yields a circular plot that provides a measure of the refractive state. It is claimed that this method is sufficiently accurate to provide a clinical determination of the refractive state of the eye.

Bostrom et al. (1978) have attempted to replicate Regan's experiments by means of a superior, commercial lock-in amplifier. They find that although the sensitivity of the system may reach that found by Regan, the reliability or repeatability of the results is not adequate for routine clinical use. Erratic changes in amplitude can be observed that appear to be caused by slight variations in the VEP output frequency when fed into a very small bandpass, high-Q circuit. The frequency may, for example, change by only 0.1 Hz. The period difference between 6.0 Hz and 6.1 Hz is 3 msec. This is only 1 to 3% of the transmission time. A biological system is unlikely to maintain a conduction velocity with such a high degree of stability. Regan's system is less sharply tuned ($Q = 64$) than the one used by Bostrom et al. ($Q = 240$). They found that only noise resulted with a lower Q.

Visual Acuity

The evoked potential can be used to measure visual acuity objectively. An older objective method of determining visual acuity, the employment of optokinetic nystagmus, is difficult to use and of questionable validity (Marg et al. 1976).

Campbell and Maffei (1970) showed that the absolute-contrast threshold of the visual evoked potential coincided with the psychophysical absolute threshold. At threshold, when a grating was visible, it would produce an evoked potential but the same stimulus would give no clear response when it was not seen (Campbell and Kulikowski 1972). A similar reduction in meridional amblyopia (low visual acuity) and the same meridional evoked potential was shown by Freeman and Thibos (1973). Berkley and Watkins (1973) demonstrated in the cat that visual acuity could be measured by evoked potentials by variations in the spatial frequency of the stimulus. This experiment was followed by measurement of the development of acuity in growing kittens (Freeman and Marg 1975).

Application of these methods in the nursery yielded data that showed that normal healthy infants reach the normal adult level of acuity (20/20 or 30 cycles/degree) at around 5 months of age (Marg et al. 1976, Marg and Freeman 1976).

Marg and Freeman (1977) found that the agreement between the common standard psychophysical method with Snellen letters and with gratings eliciting evoked potentials was mainly within ±7 cycles/degree. Some of the eyes had slightly reduced vision because of chronic disease (Fig. 7-8). This agreement is within about one line on standard visual-acuity charts, which is normally the maximum error of clinical measurement. Thus these 15 subjects (6 normal and 9 abnormal) demonstrated reasonably good clinical agreement between the subjective and objective measures of acuity. Independently, Grall et al. (1976) found similar results.

Evoked potential measurement of acuity may also shed light on visual development problems in regard to visual deprivation which causes amblyopia and may cause squint. These measurements provide a powerful tool for the clinician and the neurophysiologist. Modern electrical engineering and computer science has made them possible and it is expected that they will become more widely employed in the near future.

Summary and Conclusions

Although the visual evoked potential holds great promise as a clinical tool for determining the refractive state of the eye, it is neither sufficiently fast nor accurate to be used in a routine manner. It can be of value for selected patients who require special diagnosis such as for the patency of the visual pathways, and for the diagnosis of certain diseases that effect the visual system such as multiple sclerosis (Zeese 1977). In special cases it may be helpful in determining the refractive state, along with retinoscopy. It also can be used to determine visual acuity objectively, which is of particular importance in infants and others who cannot or do not give reliable subjective responses. In principle visual evoked potential refraction should be superior to all other objective methods, but it is not so in practice. Further development of the field where the advantages of these principles are realized may one day make it routinely useful in refractive examinations. At present, evoked potentials are firmly established as an important diagnostic tool for certain specific problems of vision and the nervous system.

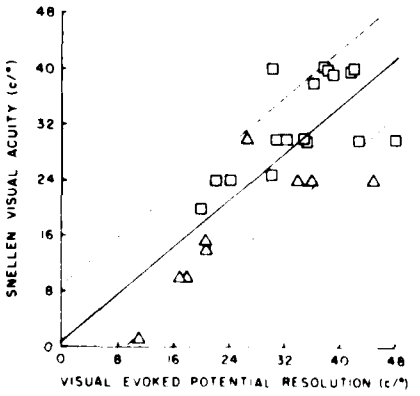

FIG. 7-8. Relationship between Snellen visual acuity and evoked potential resolution. Squares represent normal eyes; triangles represent those with some chronic pathological process such as glaucoma, macular degeneration, etc. There is good clinical agreement within ±7 cycles per degree, between the dashed lines, or approximately one line on the standard visual acuity chart) for most of these measurements. (From Marg and Freeman 1977.)

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EPILOG

Computer-actuated Refractor III Prime

While this book was being typeset, the new developments outlined in Chap. 6 were in progress and have now been completed. Refractor III Prime (Plates K and L) has the range of the older model but with all the improvements in design that were discussed.

The system is smaller (largest dimension 24 in.), lighter (52 lb), and more reliable than seemed possible just a few years ago. Power consumption (typically 8 to 25 W for the refractor and less than 500 W total) is a fraction of the previous level. The refractor is faster (worst-case movement time less than 1 sec at low speed), and quieter, and has met or exceeded the design goals to make it a practical, clinical instrument, easy to maintain and, if necessary, to service. Stepping motors control the axes and dc motors turn the lens disks.

We have also installed dual floppy disks, microprocessor-controlled retroilluminated displays, microprocessor interface, and a single-board computer featuring an Intersil IM6100 microprocessor in place of a PDP-8/E. The electronic circuit boards and power supplies fit into one box with the dual floppy disks. The box can fit into a standard 19-in.-wide rack and is 11 in. high and 34 in. deep. The front of the box has a two-line display of 24 alphanumeric characters each for lens power readout.

The distance retroilluminated display is about 39 in. square and 4 in. deep. It employs long-life miniature incandescent lamps controlled by a microprocessor.

We who have worked on the project over the years feel that this is the fruit of our labor. Naturally we shall find ways and means for further improvement. But at this stage we have a practical and useful instrument that we expect will launch eye refraction examinations into the computer age.

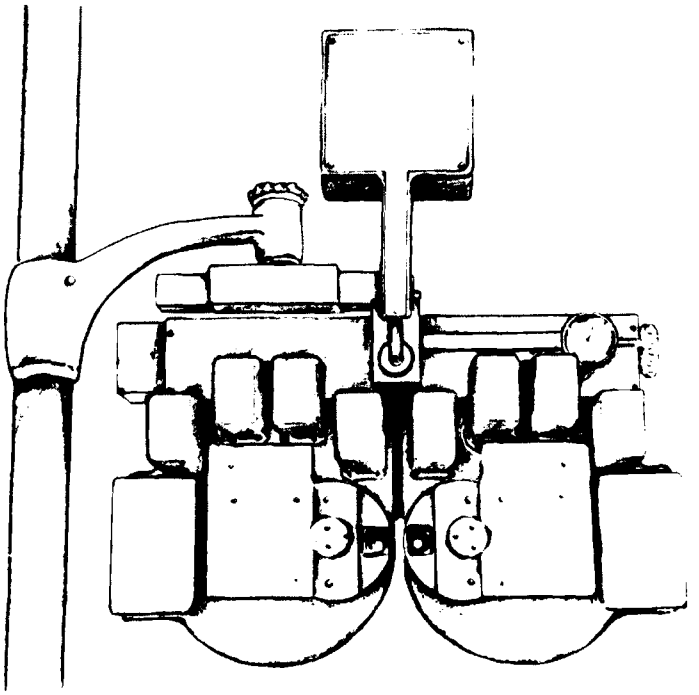


PLATE J. Refractor III Prime

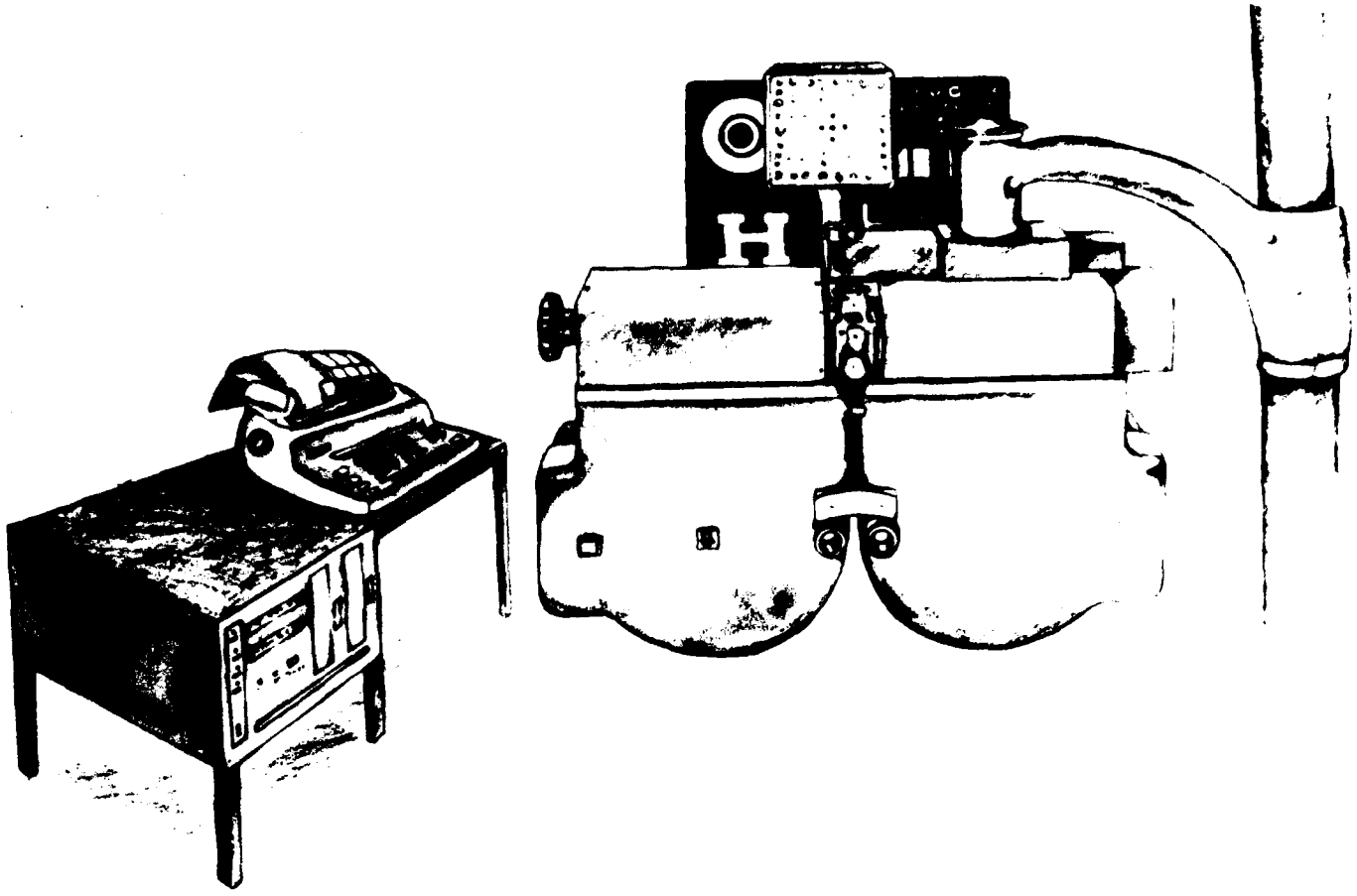
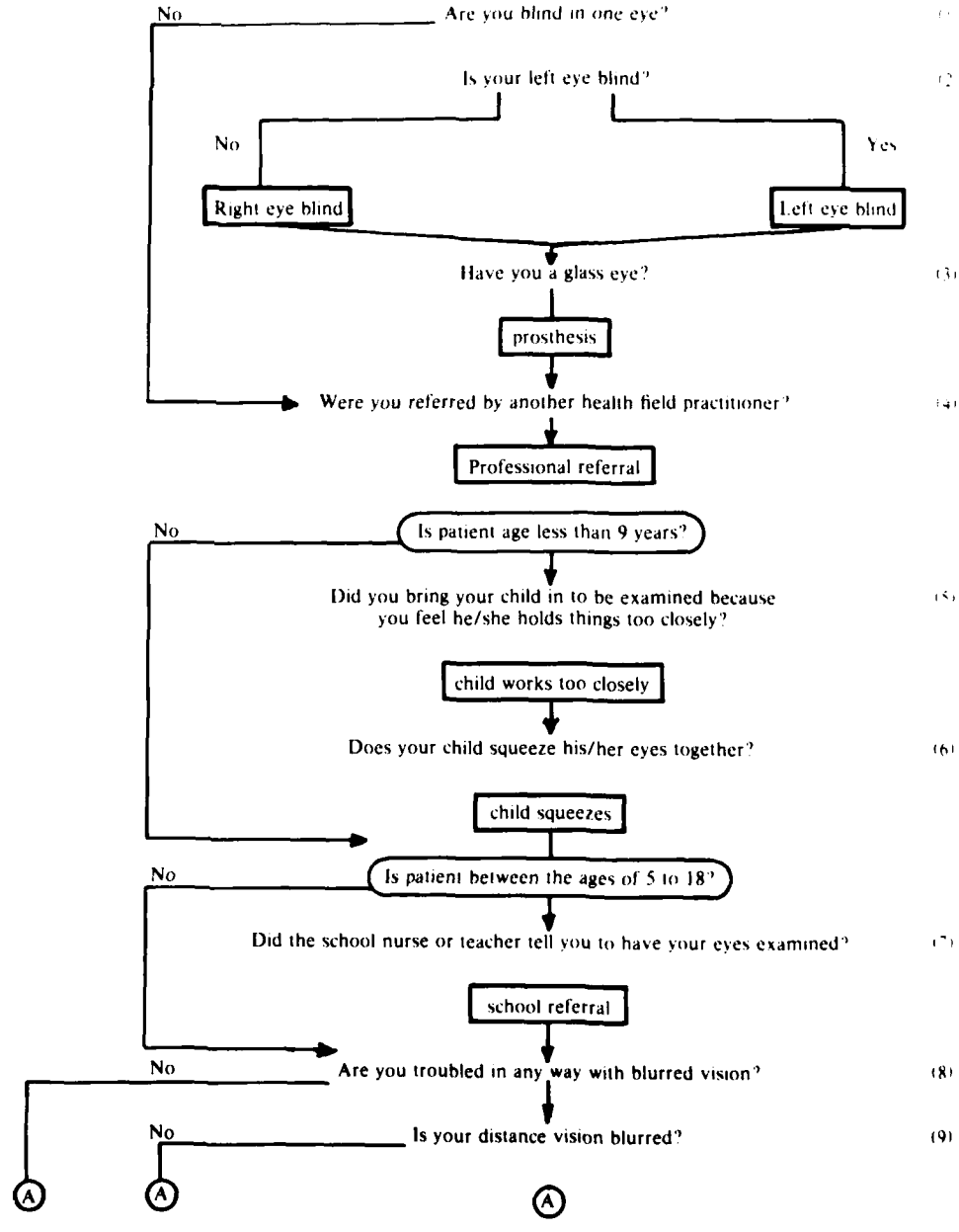
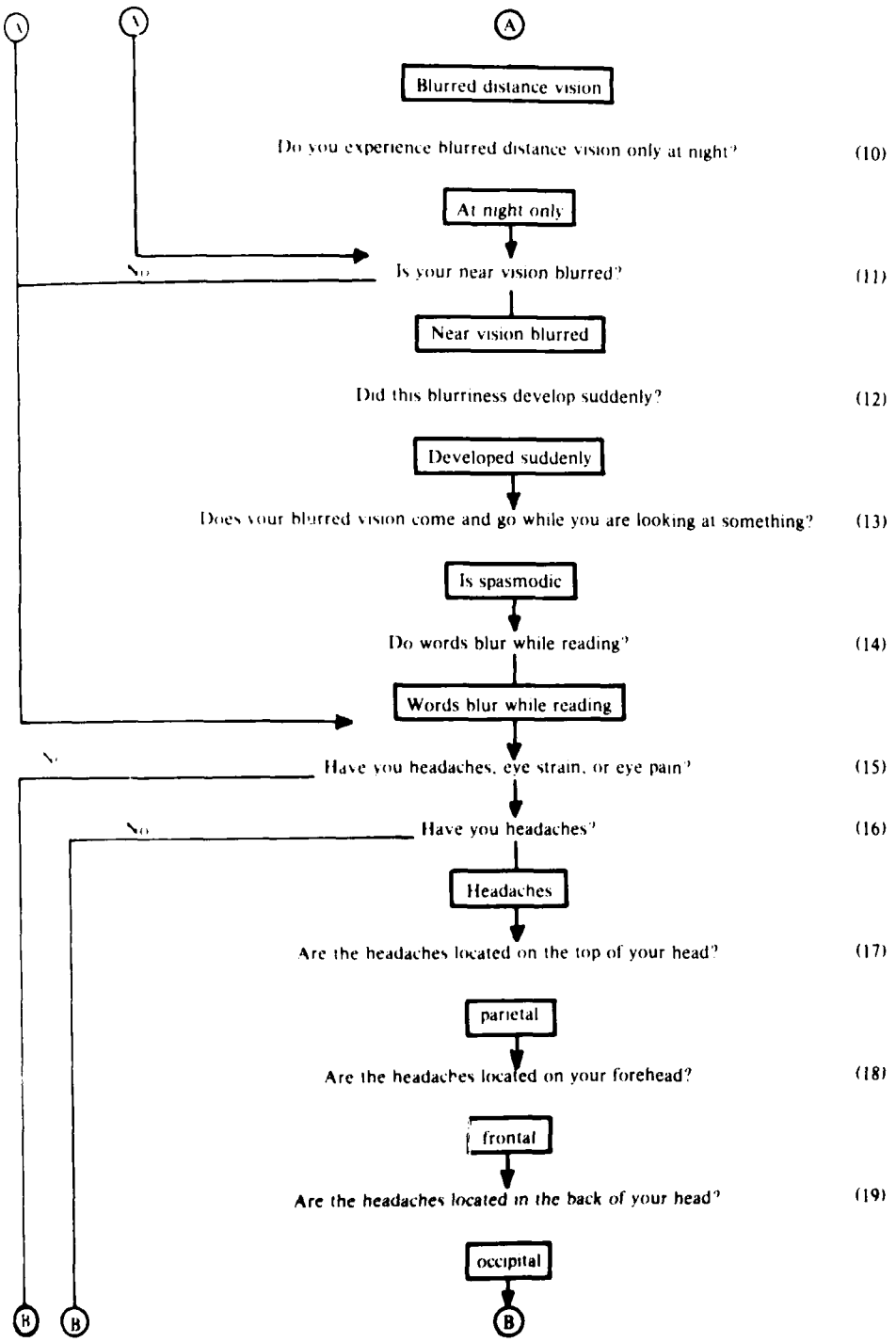


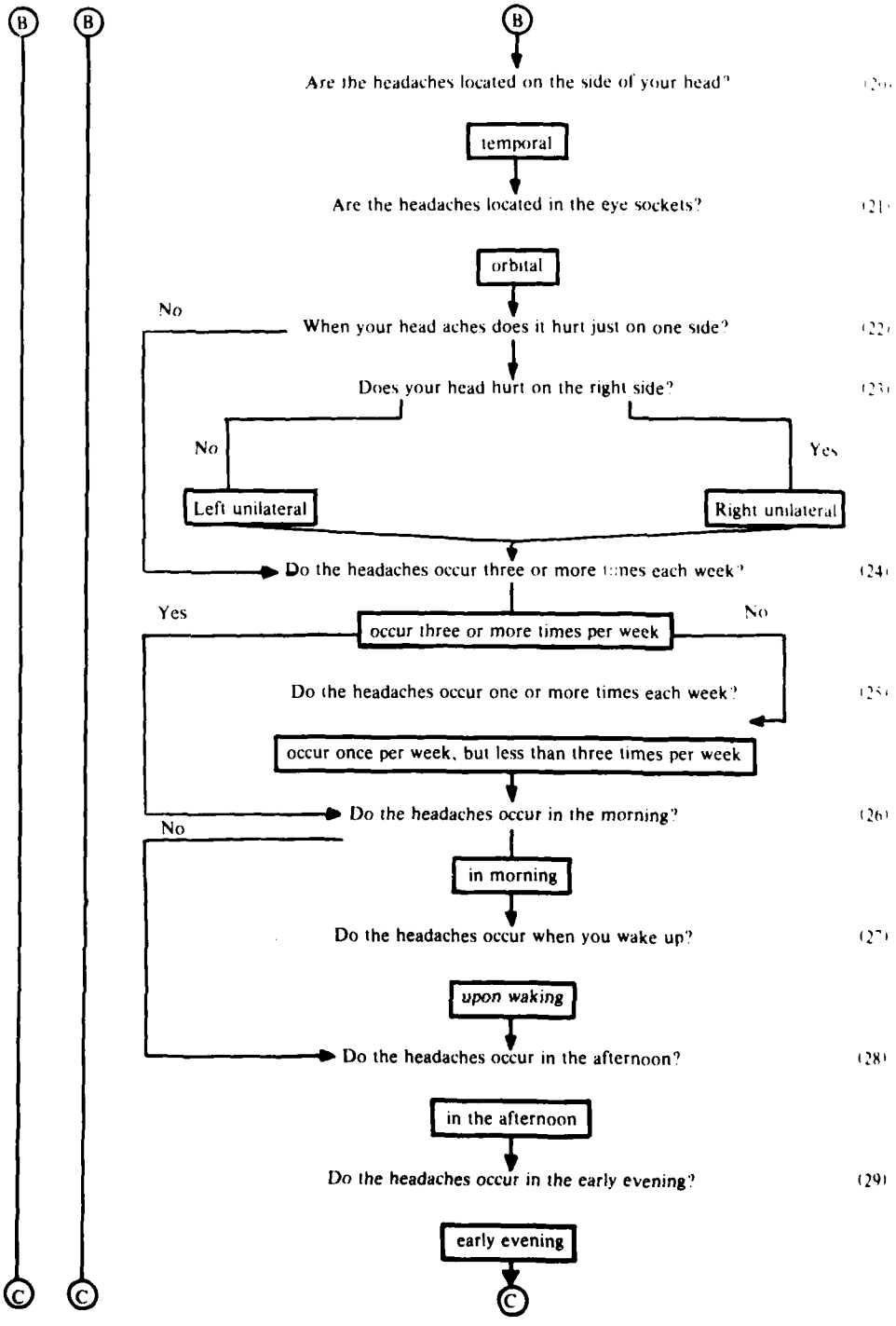
PLATE K Complete Refractor III Prime system

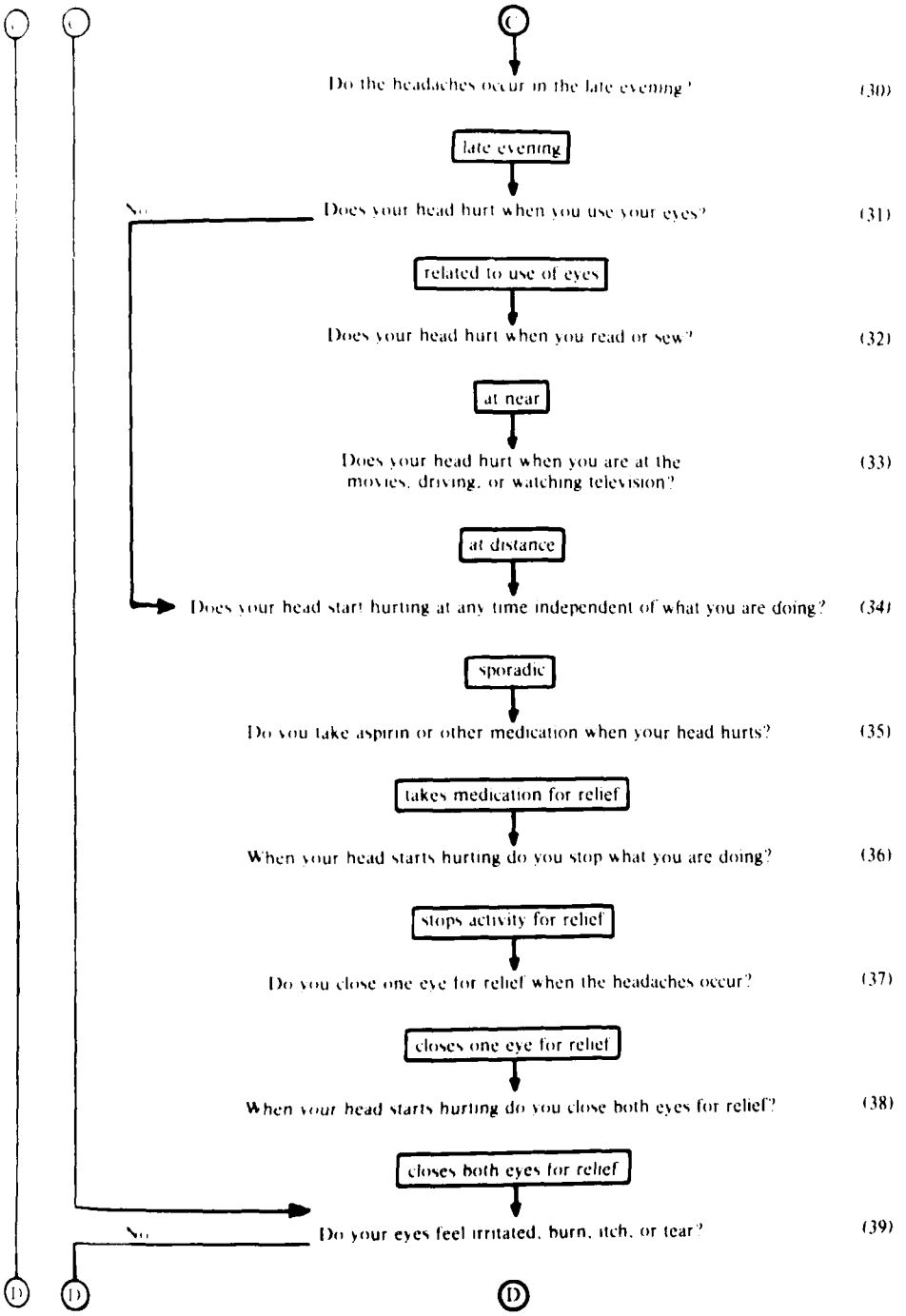
Appendix I
CASE HISTORY FLOW CHART*

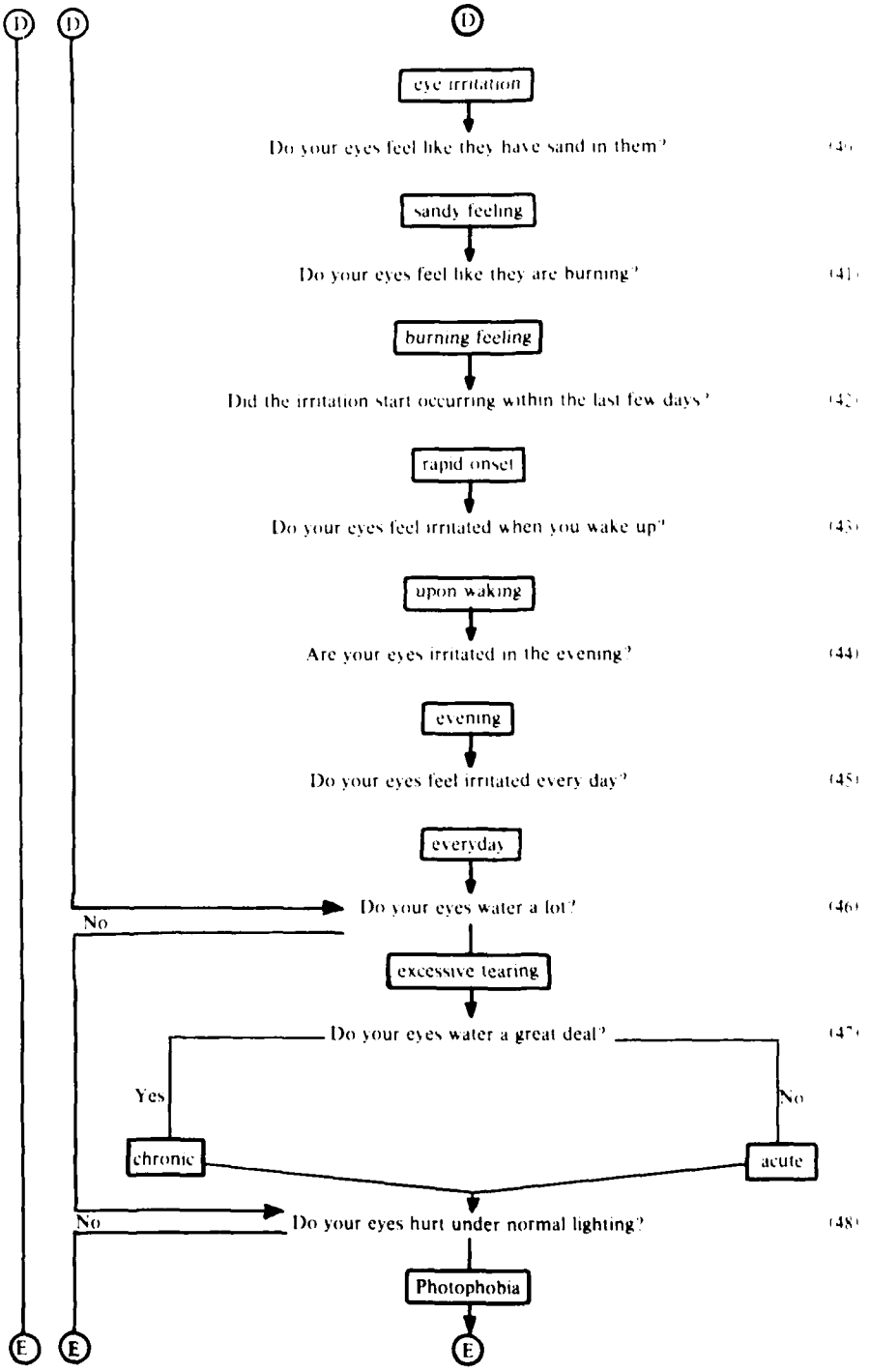


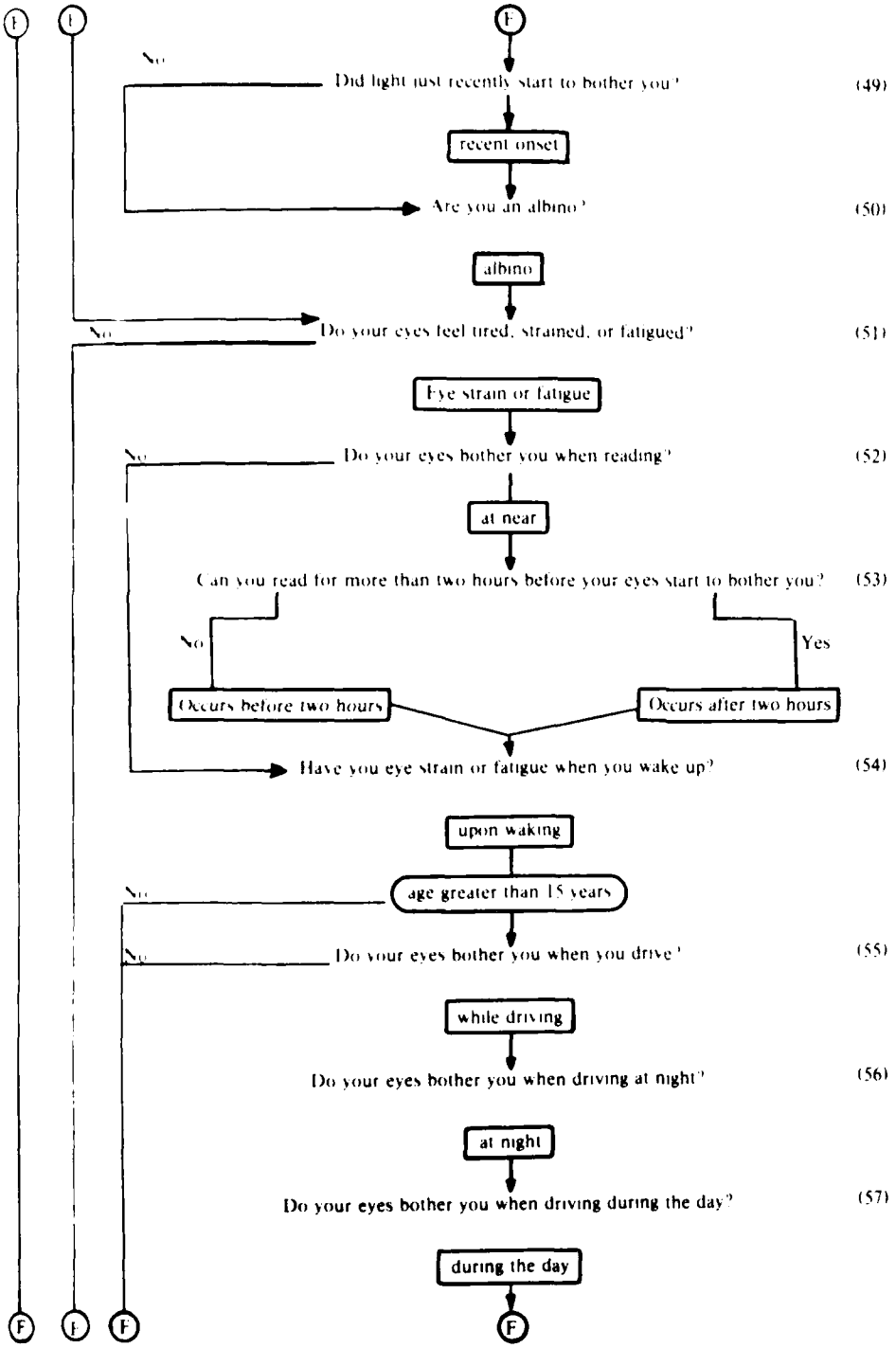
*Rectangular boxes are patient's answers; round boxes are questions answered from data in the computer

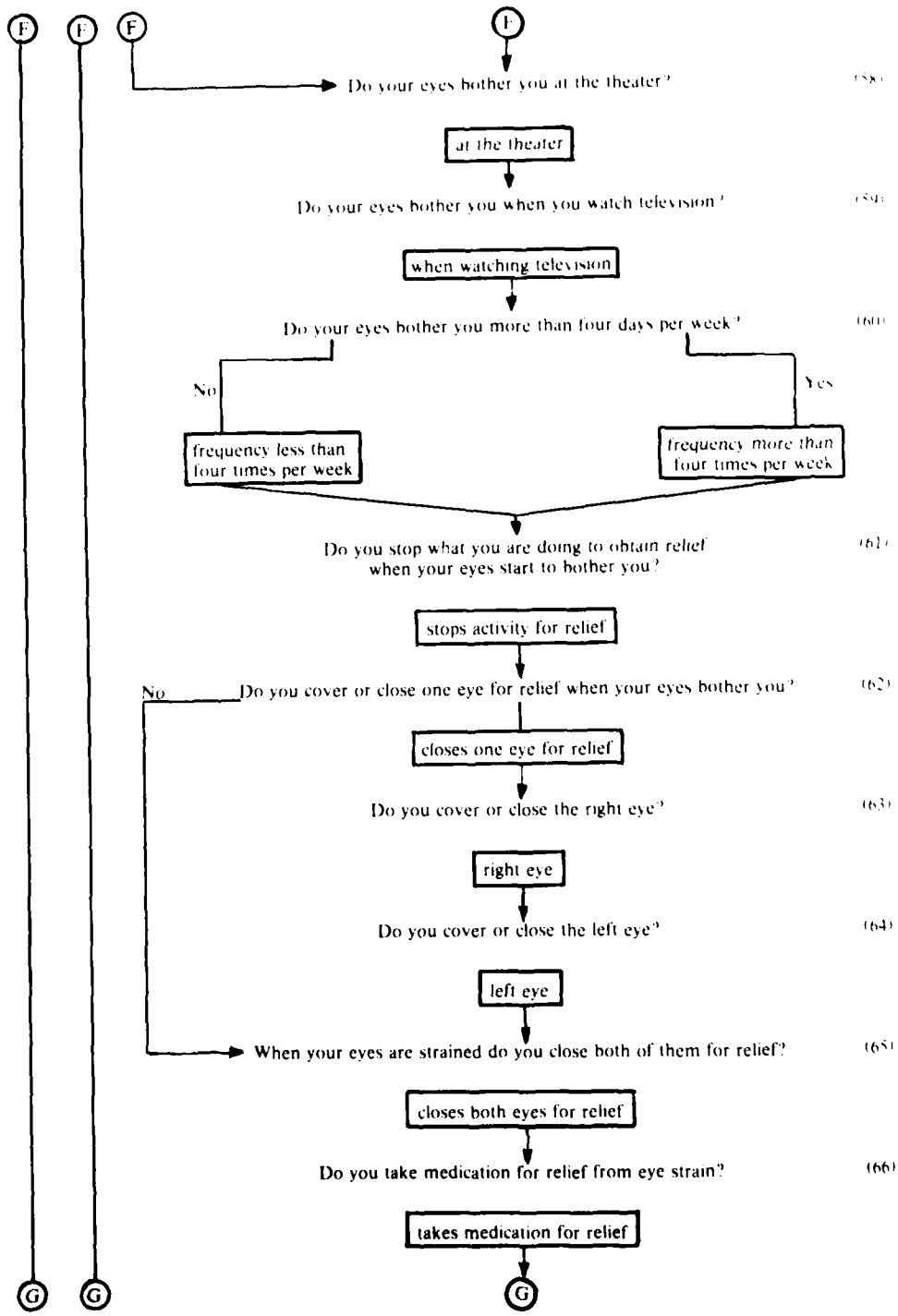

A
Blurred distance vision
Do you experience blurred distance vision only at night? (10)
At night only
No
Is your near vision blurred? (11)
Near vision blurred
Did this blurriness develop suddenly? (12)
Developed suddenly
Does your blurred vision come and go while you are looking at something? (13)
Is spasmodic
Do words blur while reading? (14)
Words blur while reading
No
Have you headaches, eye strain, or eye pain? (15)
No
Have you headaches? (16)
Headaches
Are the headaches located on the top of your head? (17)
parietal
Are the headaches located on your forehead? (18)
frontal
Are the headaches located in the back of your head? (19)
occipital
B
B
B

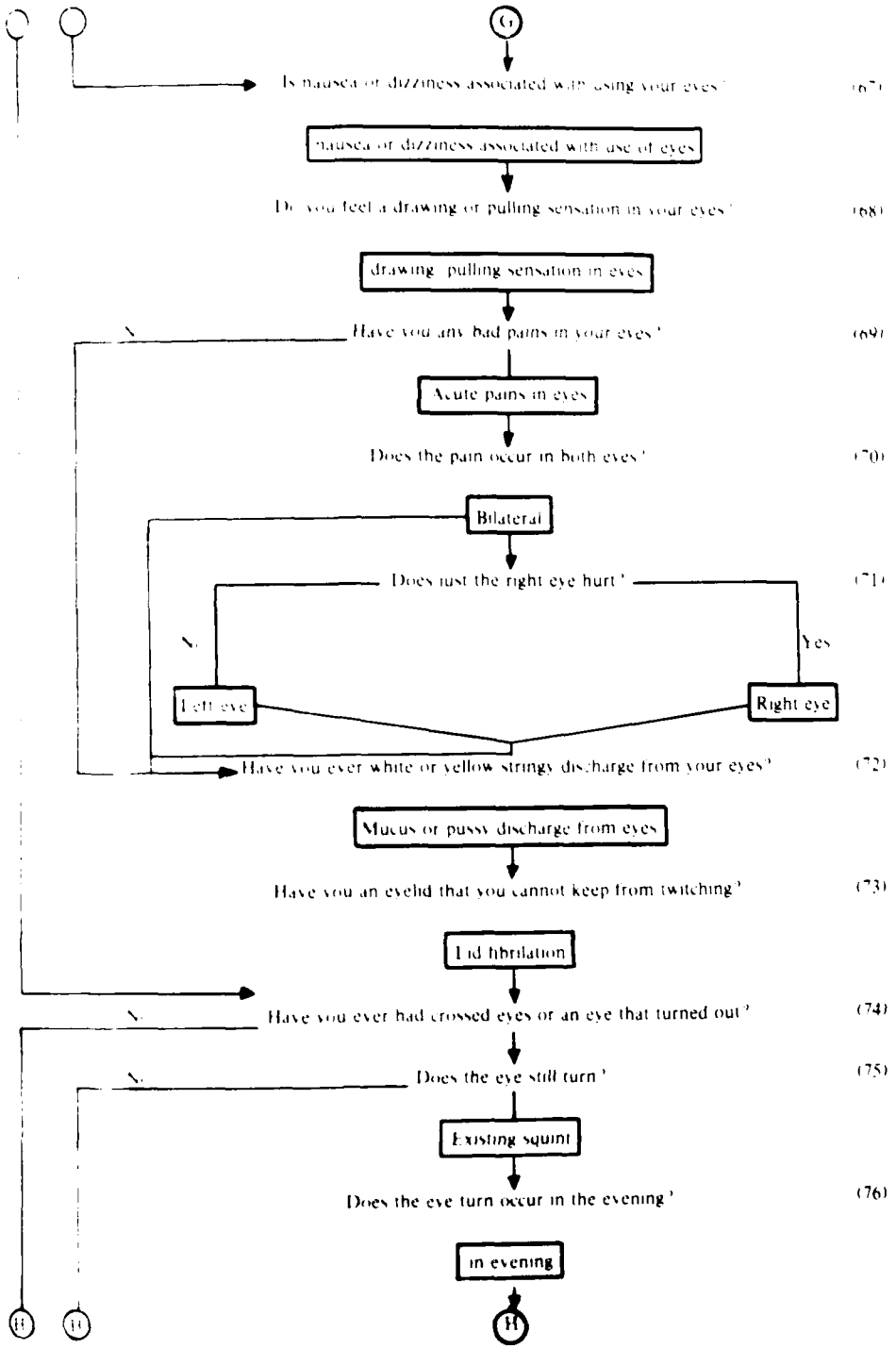

B
B
B
Are the headaches located on the side of your head?
temporal
Are the headaches located in the eye sockets?
orbital
No
When your head aches does it hurt just on one side?
Does your head hurt on the right side?
No
Yes
Left unilateral
Right unilateral
Do the headaches occur three or more times each week?
Yes
occur three or more times per week
No
Do the headaches occur one or more times each week?
occur once per week, but less than three times per week
Do the headaches occur in the morning?
No
in morning
Do the headaches occur when you wake up?
upon waking
Do the headaches occur in the afternoon?
in the afternoon
Do the headaches occur in the early evening?
early evening
C
C
C

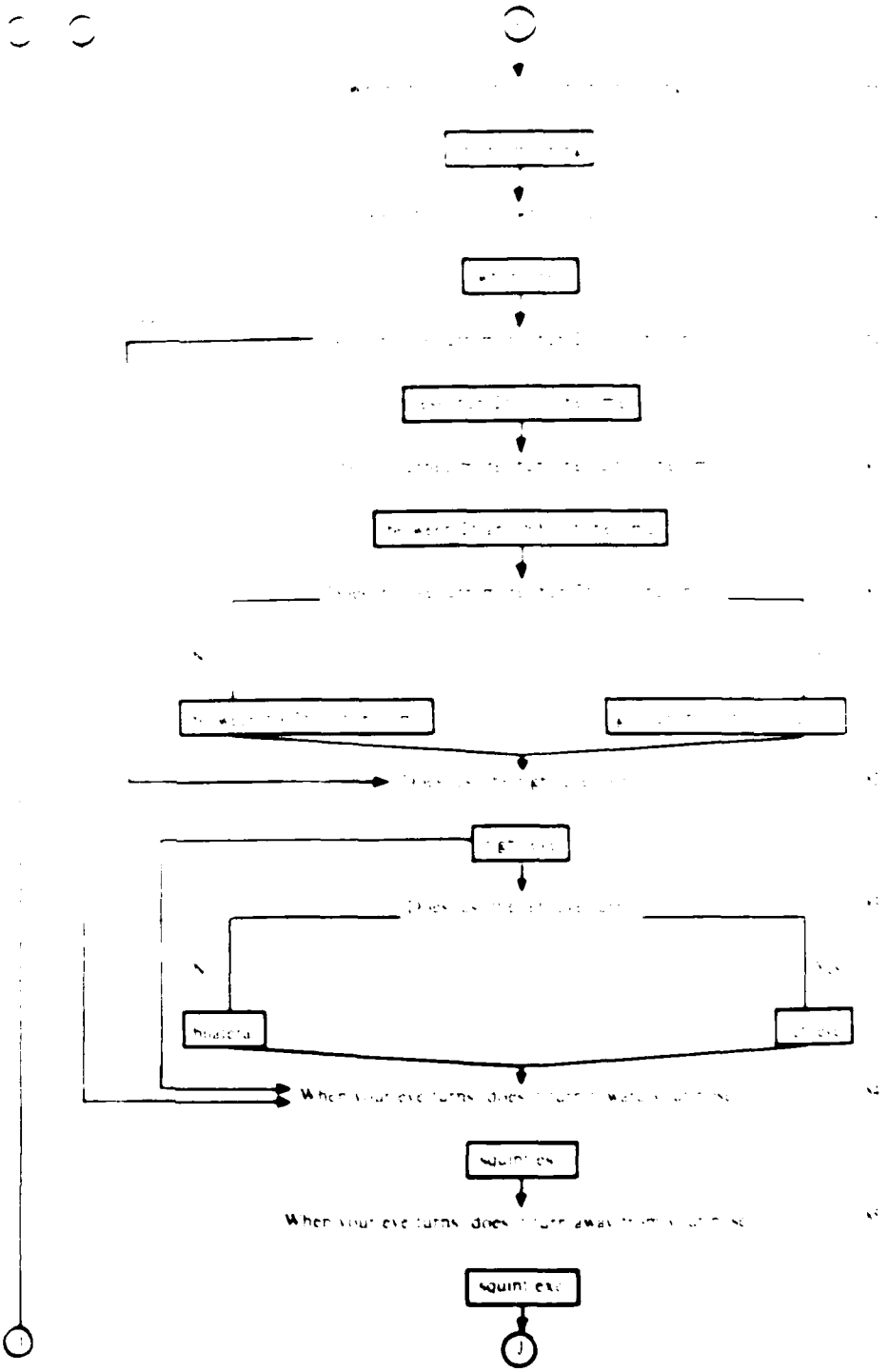

C
Do the headaches occur in the late evening? (30)
late evening
No
Does your head hurt when you use your eyes? (31)
related to use of eyes
Does your head hurt when you read or sew? (32)
at near
Does your head hurt when you are at the movies, driving, or watching television? (33)
at distance
Does your head start hurting at any time independent of what you are doing? (34)
sporadic
Do you take aspirin or other medication when your head hurts? (35)
takes medication for relief
When your head starts hurting do you stop what you are doing? (36)
stops activity for relief
Do you close one eye for relief when the headaches occur? (37)
closes one eye for relief
When your head starts hurting do you close both eyes for relief? (38)
closes both eyes for relief
No
Do your eyes feel irritated, burn, itch, or tear? (39)
D
D
D

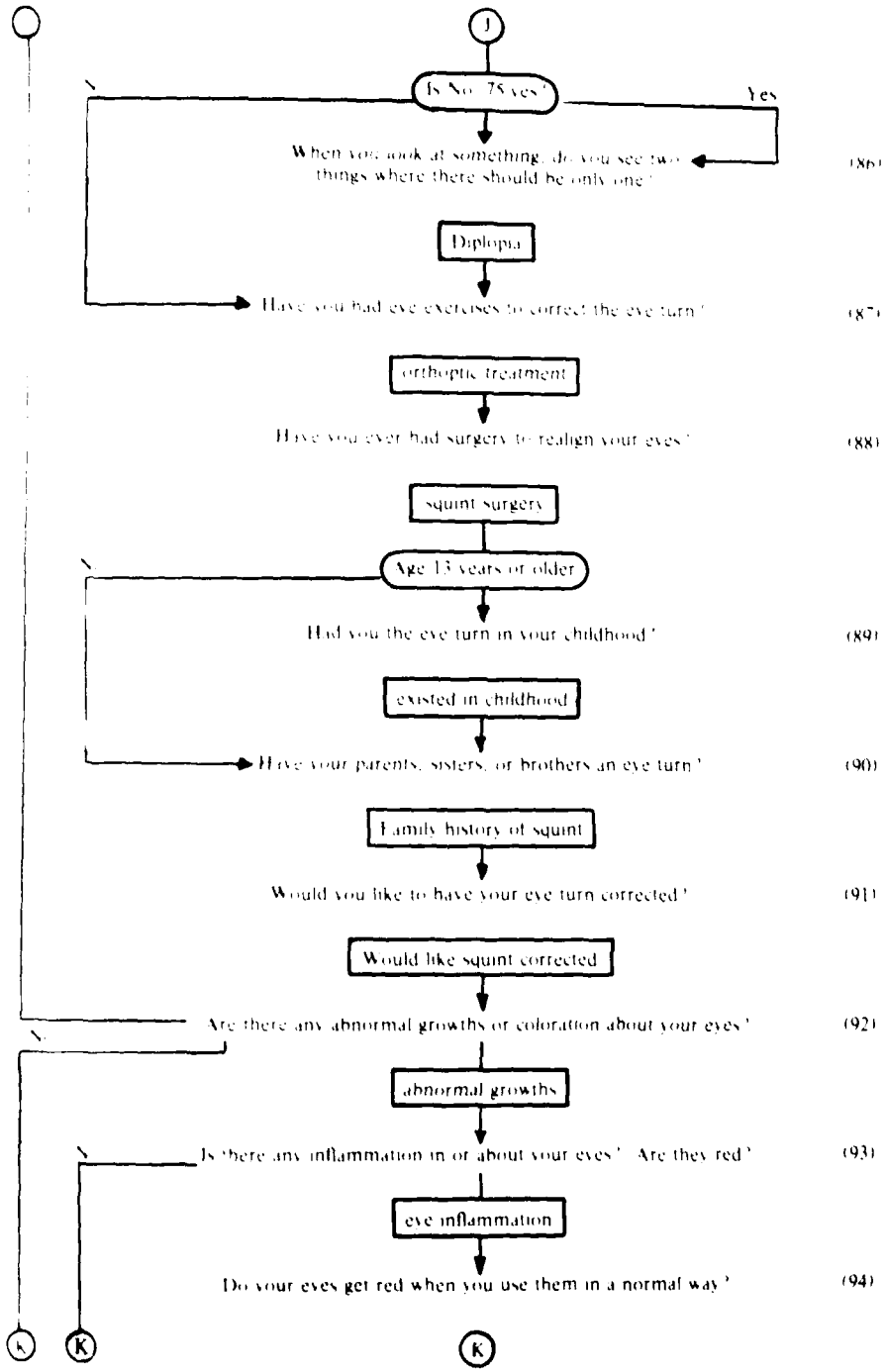

D
D
D
eye irritation
Do your eyes feel like they have sand in them?
(40)
sandy feeling
Do your eyes feel like they are burning?
(41)
burning feeling
Did the irritation start occurring within the last few days?
(42)
rapid onset
Do your eyes feel irritated when you wake up?
(43)
upon waking
Are your eyes irritated in the evening?
(44)
evening
Do your eyes feel irritated every day?
(45)
everyday
Do your eyes water a lot?
(46)
No
excessive tearing
Do your eyes water a great deal?
(47)
Yes
No
chronic
acute
No
Do your eyes hurt under normal lighting?
(48)
Photophobia
E
E
E

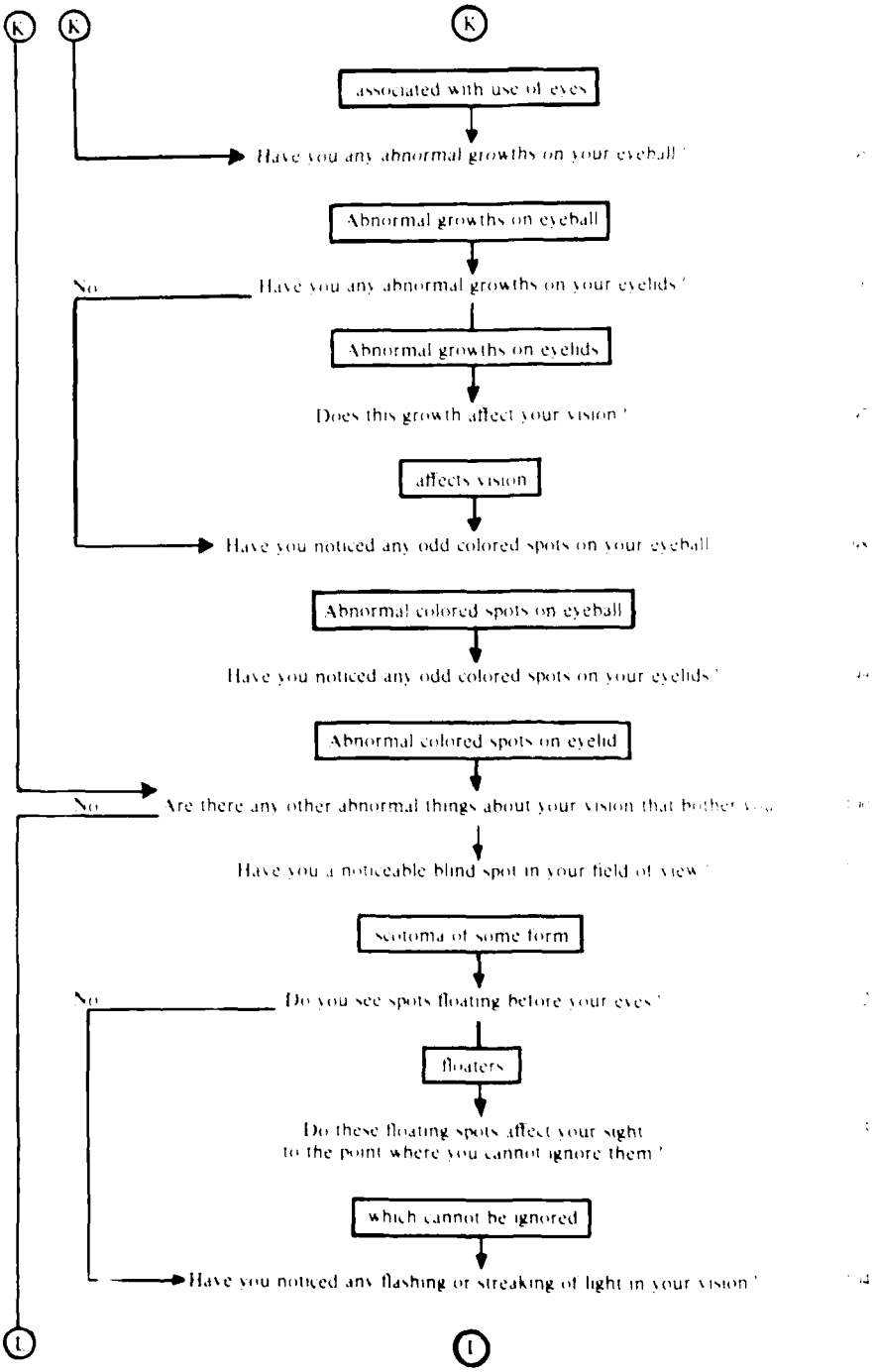

F
No
Did light just recently start to bother you? (49)
recent onset
Are you an albino? (50)
albino
Do your eyes feel tired, strained, or fatigued? (51)
No
Eye strain or fatigue
No
Do your eyes bother you when reading? (52)
at near
Can you read for more than two hours before your eyes start to bother you? (53)
No
Yes
Occurs before two hours
Occurs after two hours
Have you eye strain or fatigue when you wake up? (54)
upon waking
No
age greater than 15 years
No
Do your eyes bother you when you drive? (55)
while driving
Do your eyes bother you when driving at night? (56)
at night
Do your eyes bother you when driving during the day? (57)
during the day
F

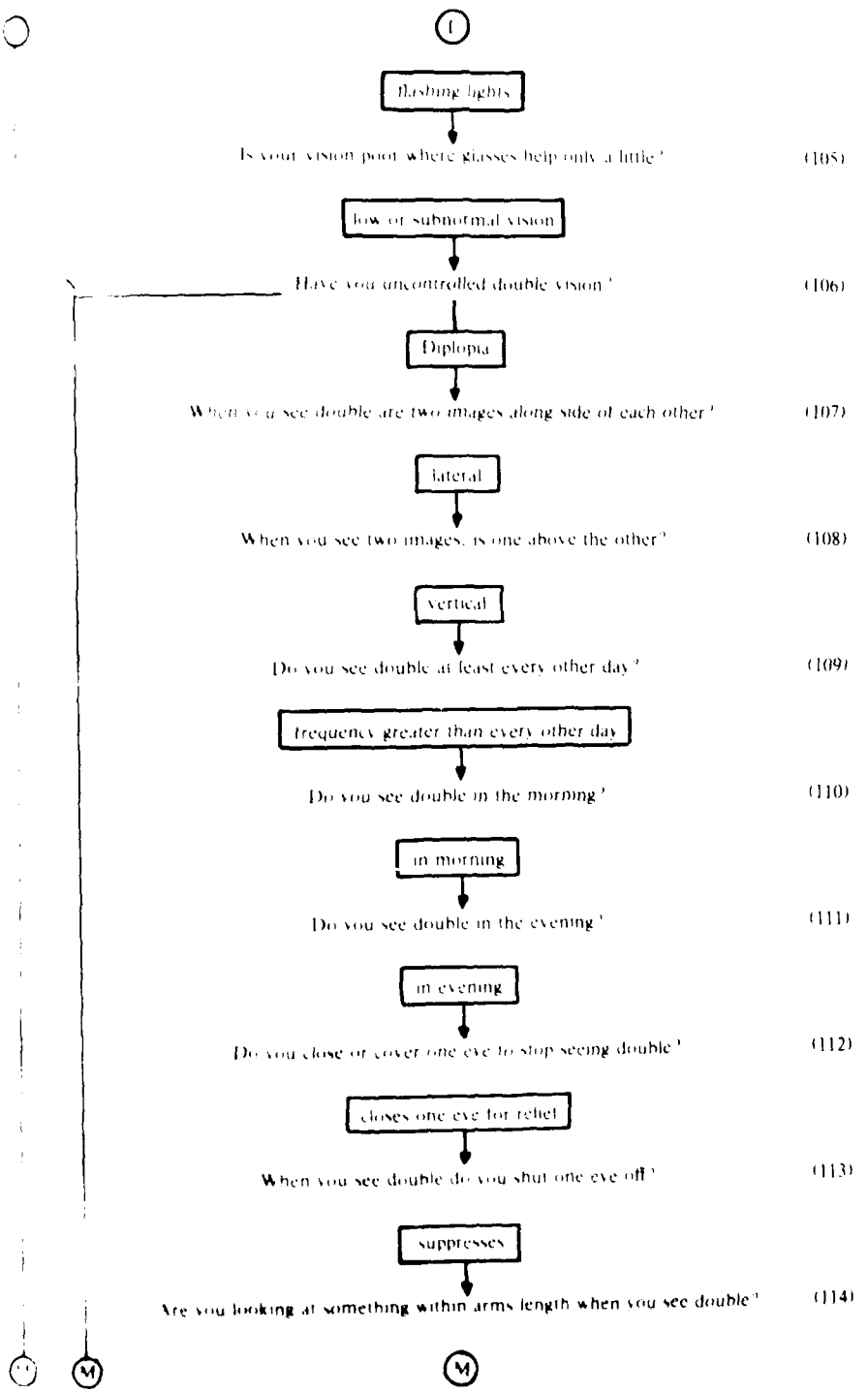

F
F
F
E
Do your eyes bother you at the theater?
(58)
at the theater
Do your eyes bother you when you watch television?
(59)
when watching television
Do your eyes bother you more than four days per week?
(60)
No
Yes
frequency less than four times per week
frequency more than four times per week
Do you stop what you are doing to obtain relief when your eyes start to bother you?
(61)
stops activity for relief
No
Do you cover or close one eye for relief when your eyes bother you?
(62)
closes one eye for relief
Do you cover or close the right eye?
(63)
right eye
Do you cover or close the left eye?
(64)
left eye
When your eyes are strained do you close both of them for relief?
(65)
closes both eyes for relief
Do you take medication for relief from eye strain?
(66)
takes medication for relief
G
G
G

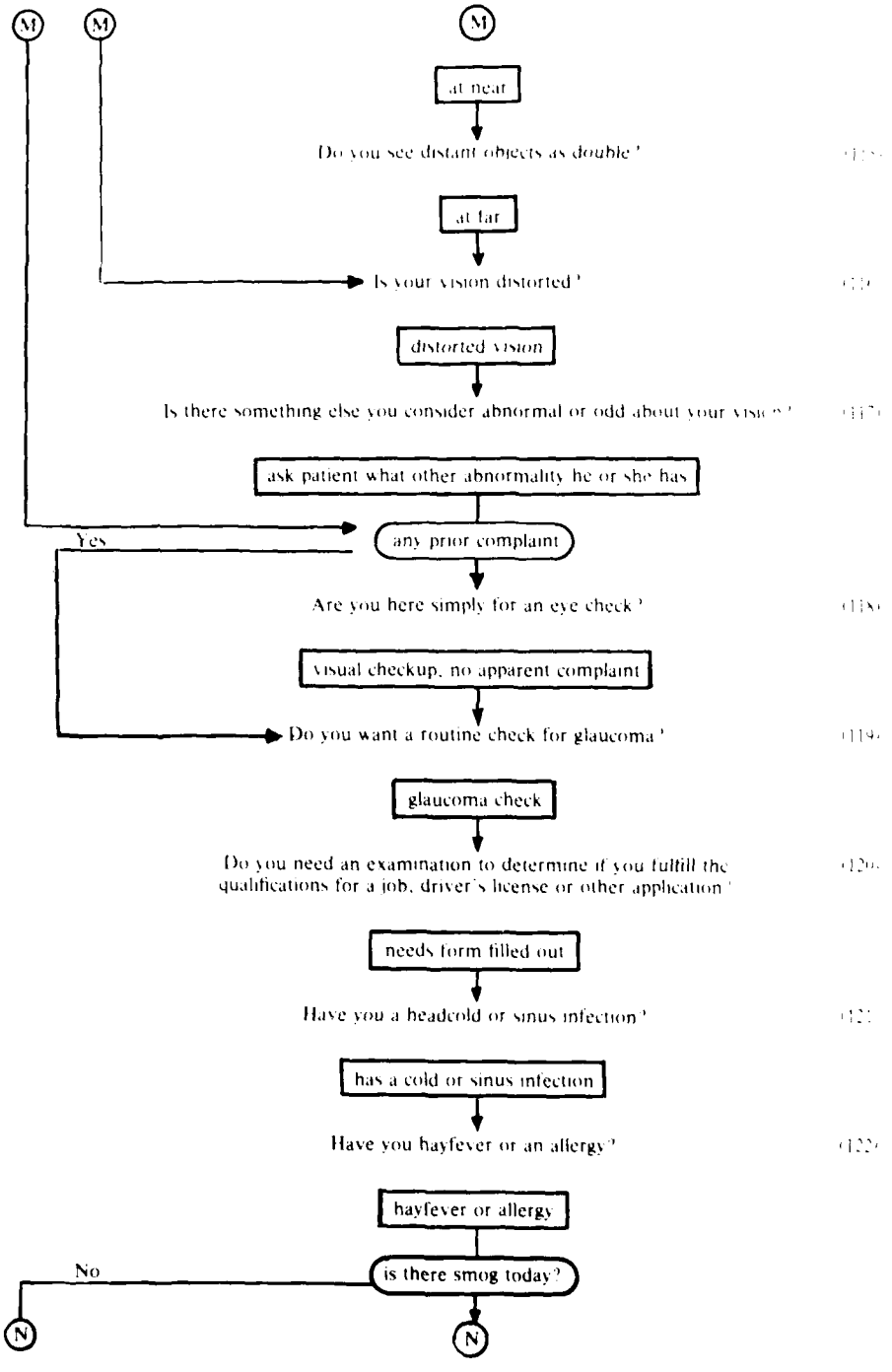

G
Is nausea or dizziness associated with use of eyes' (67)
nausea or dizziness associated with use of eyes
Do you feel a drawing or pulling sensation in your eyes' (68)
drawing pulling sensation in eyes
N
Have you any bad pains in your eyes' (69)
Acute pains in eyes
Does the pain occur in both eyes' (70)
Bilateral
Does just the right eye hurt' (71)
N
Yes
Left eye
Right eye
Have you ever white or yellow stringy discharge from your eyes' (72)
Mucus or pussy discharge from eyes
Have you an eyelid that you cannot keep from twitching' (73)
Lid fibrilation
N
Have you ever had crossed eyes or an eye that turned out' (74)
N
Does the eye still turn' (75)
Existing squint
Does the eye turn occur in the evening' (76)
in evening
H
H
H

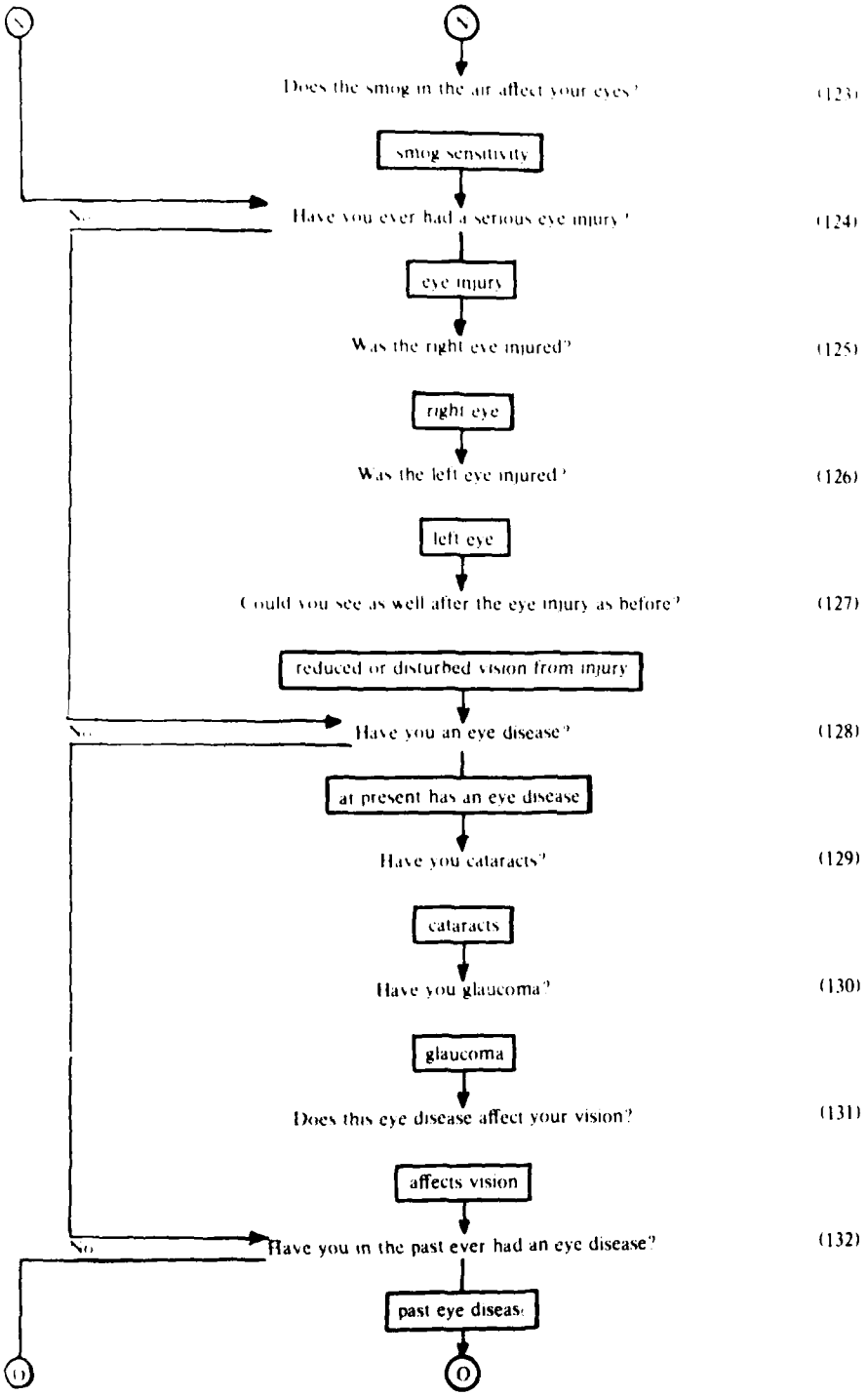

squint eye
squint eye
J

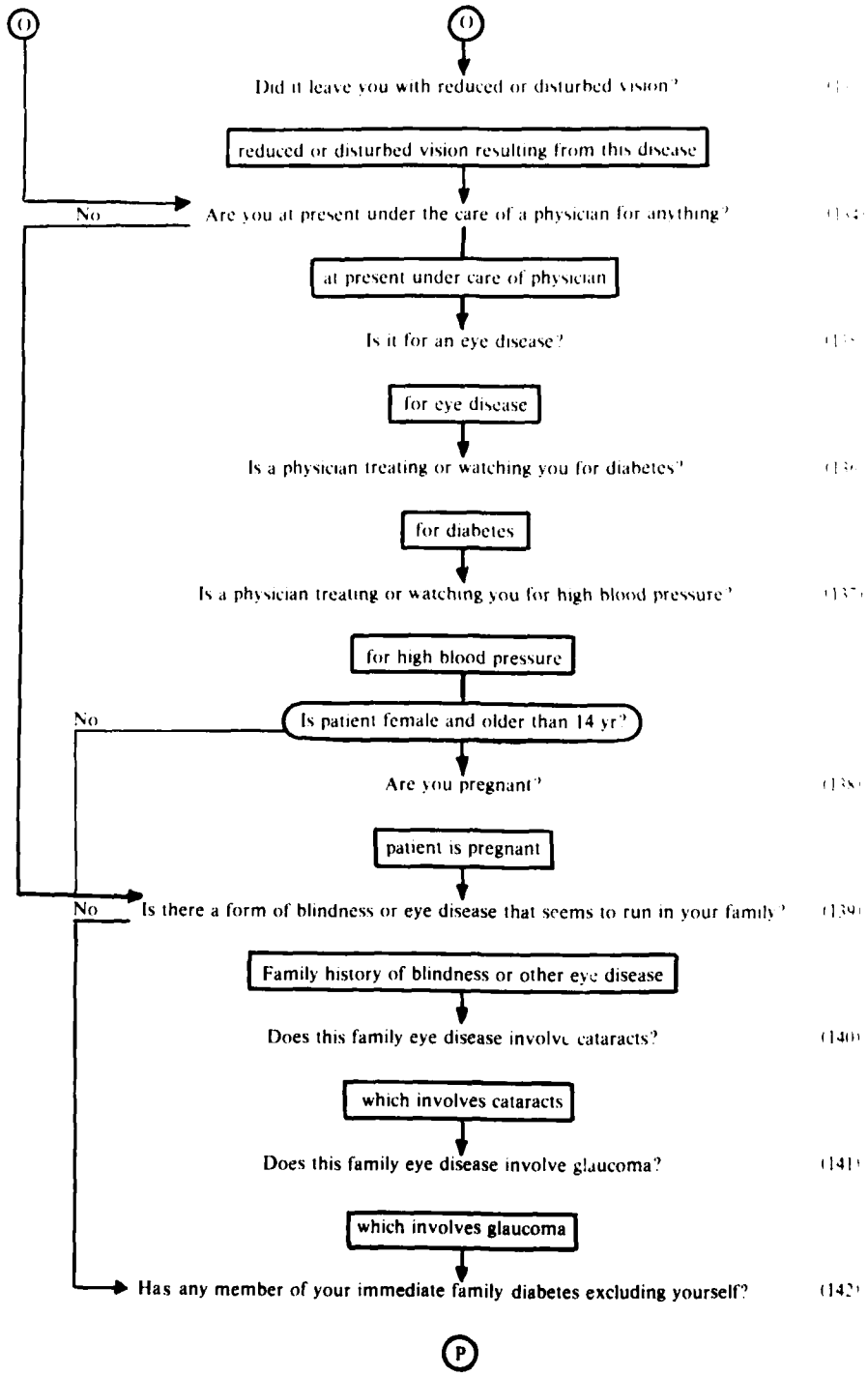

J
Is No. 75 yes?
Yes
When you look at something, do you see two things where there should be only one? (86)
Diplopia
Have you had eye exercises to correct the eye turn? (87)
orthoptic treatment
Have you ever had surgery to realign your eyes? (88)
squint surgery
Age 13 years or older
Had you the eye turn in your childhood? (89)
existed in childhood
Have your parents, sisters, or brothers an eye turn? (90)
Family history of squint
Would you like to have your eye turn corrected? (91)
Would like squint corrected
Are there any abnormal growths or coloration about your eyes? (92)
abnormal growths
Is there any inflammation in or about your eyes? Are they red? (93)
eye inflammation
Do your eyes get red when you use them in a normal way? (94)
K
K
K

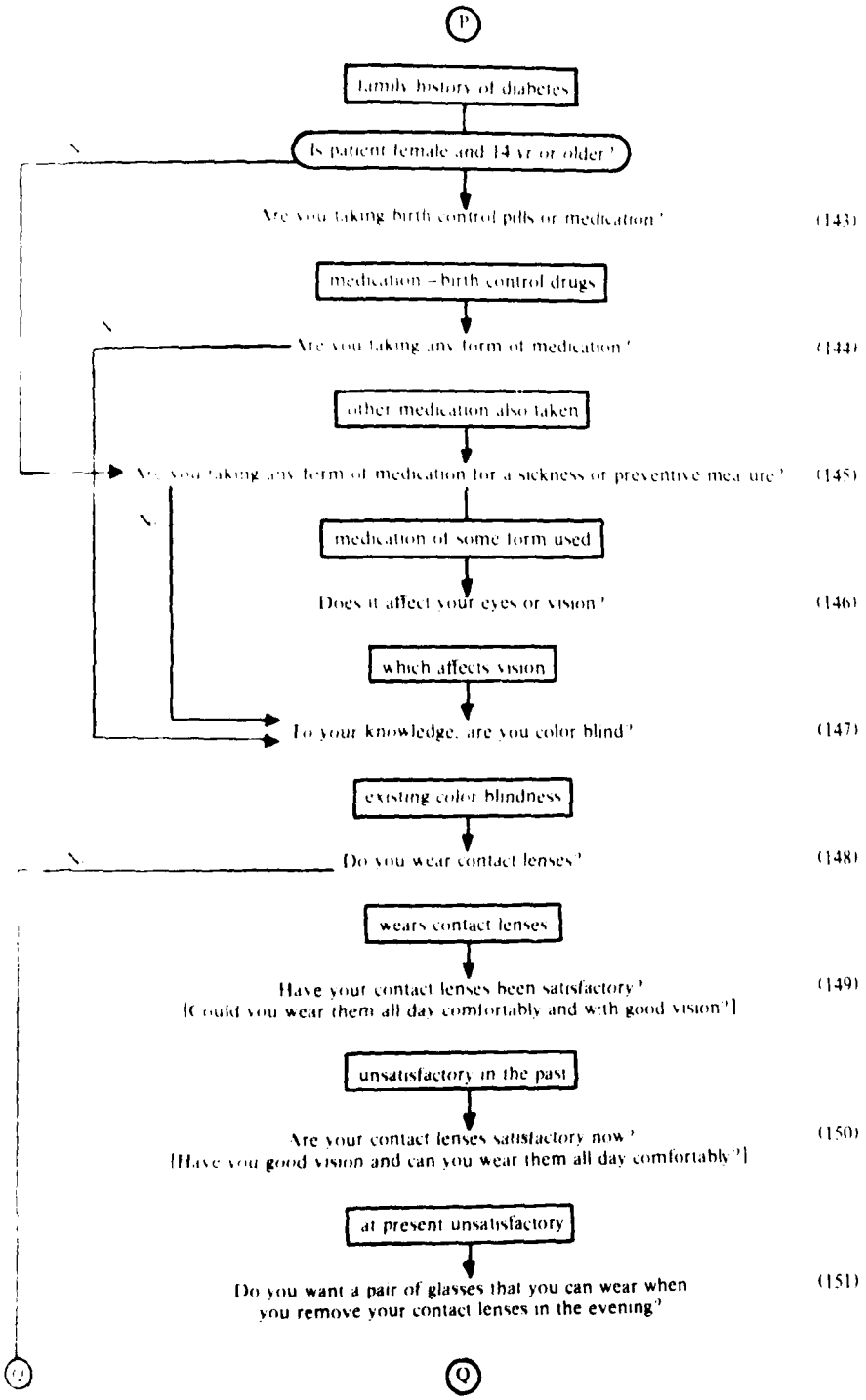

K
K
K
associated with use of eyes
Have you any abnormal growths on your eyeball
Abnormal growths on eyeball
No
Have you any abnormal growths on your eyelids
Abnormal growths on eyelids
Does this growth affect your vision
affects vision
Have you noticed any odd colored spots on your eyeball
Abnormal colored spots on eyeball
Have you noticed any odd colored spots on your eyelids
Abnormal colored spots on eyelid
No
Are there any other abnormal things about your vision that bother
Have you a noticeable blind spot in your field of view
scotoma of some form
No
Do you see spots floating before your eyes
floaters
Do these floating spots affect your sight
to the point where you cannot ignore them
which cannot be ignored
Have you noticed any flashing or streaking of light in your vision
L
L

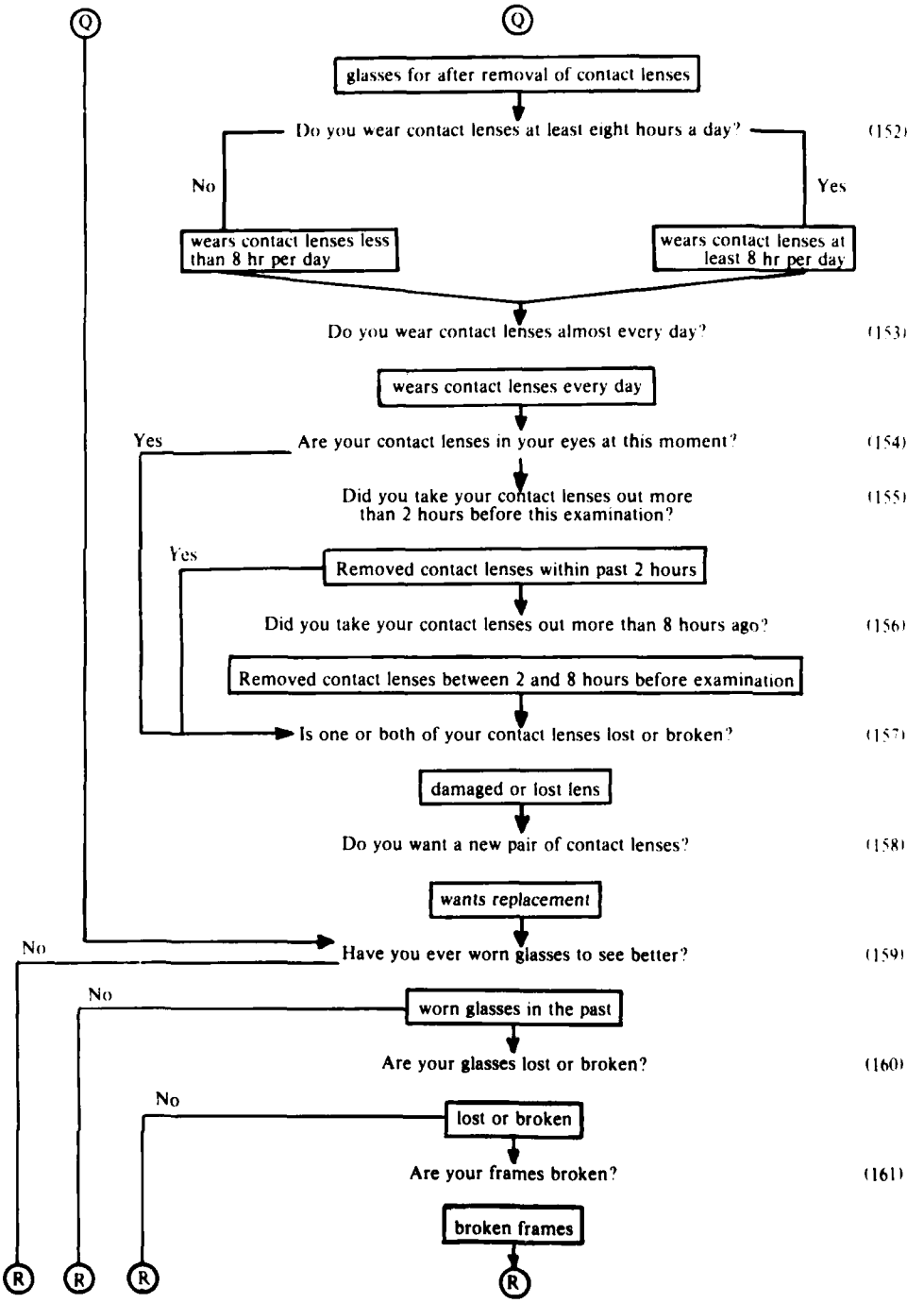

I
flashing lights
Is your vision poor where glasses help only a little? (105)
low or subnormal vision
Have you uncontrolled double vision? (106)
Diplopia
When you see double are two images along side of each other? (107)
lateral
When you see two images, is one above the other? (108)
vertical
Do you see double at least every other day? (109)
frequency greater than every other day
Do you see double in the morning? (110)
in morning
Do you see double in the evening? (111)
in evening
Do you close or cover one eye to stop seeing double? (112)
closes one eye for relief
When you see double do you shut one eye off? (113)
suppresses
Are you looking at something within arms length when you see double? (114)
M
M

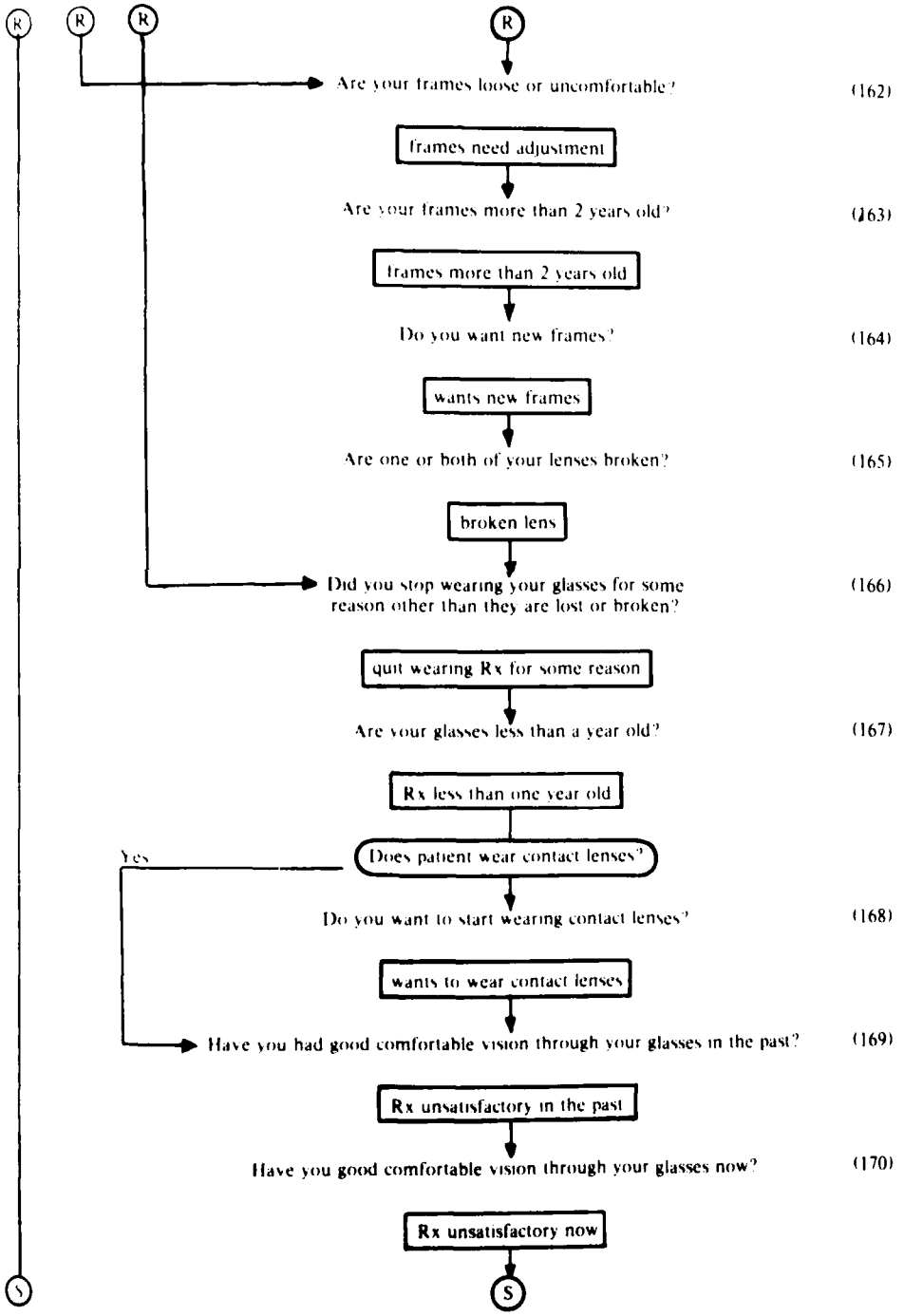

M
M
M
at near
Do you see distant objects as double?
at far
Is your vision distorted?
distorted vision
Is there something else you consider abnormal or odd about your vision?
ask patient what other abnormality he or she has
Yes
any prior complaint
Are you here simply for an eye check?
visual checkup, no apparent complaint
Do you want a routine check for glaucoma?
glaucoma check
Do you need an examination to determine if you fulfill the qualifications for a job, driver's license or other application?
needs form filled out
Have you a headcold or sinus infection?
has a cold or sinus infection
Have you hayfever or an allergy?
hayfever or allergy
No
is there smog today?
N
N

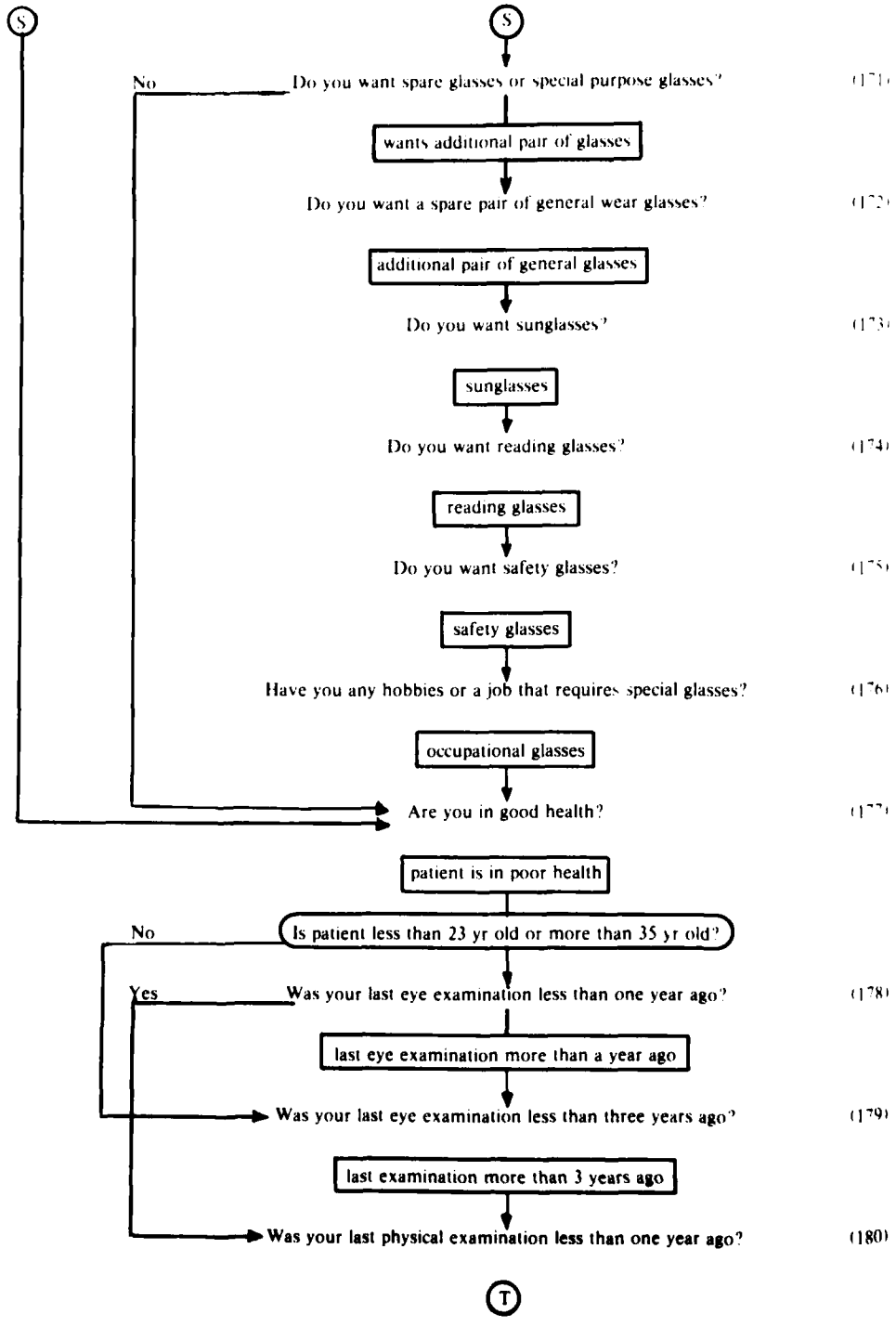

Does the smog in the air affect your eyes?
(123)
smog sensitivity
Have you ever had a serious eye injury?
(124)
eye injury
Was the right eye injured?
(125)
right eye
Was the left eye injured?
(126)
left eye
Could you see as well after the eye injury as before?
(127)
reduced or disturbed vision from injury
Have you an eye disease?
(128)
at present has an eye disease
Have you cataracts?
(129)
cataracts
Have you glaucoma?
(130)
glaucoma
Does this eye disease affect your vision?
(131)
affects vision
Have you in the past ever had an eye disease?
(132)
past eye disease

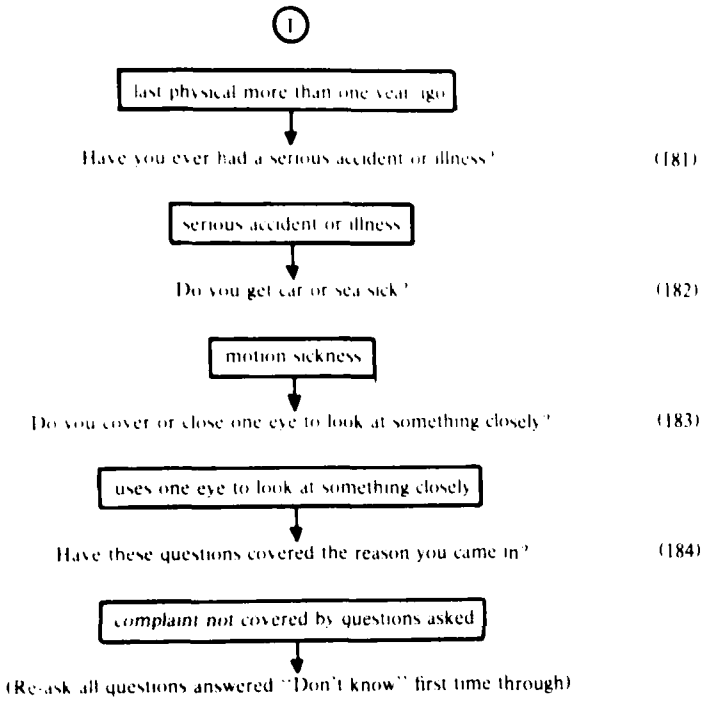

O
O
Did it leave you with reduced or disturbed vision?
reduced or disturbed vision resulting from this disease
No
Are you at present under the care of a physician for anything?
at present under care of physician
Is it for an eye disease?
for eye disease
Is a physician treating or watching you for diabetes?
for diabetes
Is a physician treating or watching you for high blood pressure?
for high blood pressure
No
Is patient female and older than 14 yr?
Are you pregnant?
patient is pregnant
No
Is there a form of blindness or eye disease that seems to run in your family?
Family history of blindness or other eye disease
Does this family eye disease involve cataracts?
which involves cataracts
Does this family eye disease involve glaucoma?
which involves glaucoma
Has any member of your immediate family diabetes excluding yourself?
P

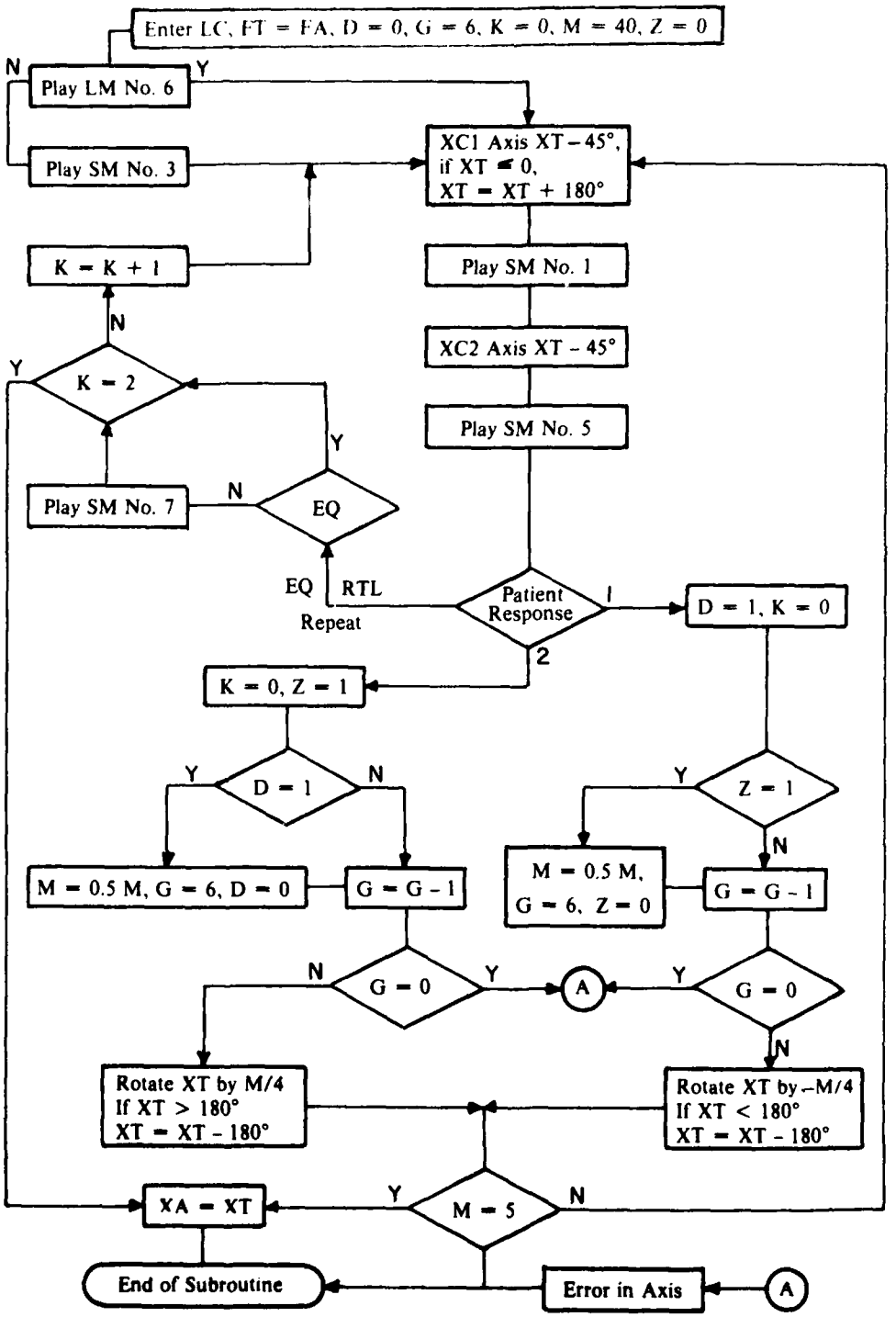

P
family history of diabetes
Is patient female and 14 yr or older?
Are you taking birth control pills or medication? (143)
medication = birth control drugs
Are you taking any form of medication? (144)
other medication also taken
Are you taking any form of medication for a sickness or preventive measure? (145)
medication of some form used
Does it affect your eyes or vision? (146)
which affects vision
To your knowledge, are you color blind? (147)
existing color blindness
Do you wear contact lenses? (148)
wears contact lenses
Have your contact lenses been satisfactory? (149)
[Could you wear them all day comfortably and with good vision?]
unsatisfactory in the past
Are your contact lenses satisfactory now? (150)
[Have you good vision and can you wear them all day comfortably?]
at present unsatisfactory
Do you want a pair of glasses that you can wear when you remove your contact lenses in the evening? (151)
Q


Q
Q
glasses for after removal of contact lenses
Do you wear contact lenses at least eight hours a day? (152)
No
Yes
wears contact lenses less than 8 hr per day
wears contact lenses at least 8 hr per day
Do you wear contact lenses almost every day? (153)
wears contact lenses every day
Yes
Are your contact lenses in your eyes at this moment? (154)
Did you take your contact lenses out more than 2 hours before this examination? (155)
Yes
Removed contact lenses within past 2 hours
Did you take your contact lenses out more than 8 hours ago? (156)
Removed contact lenses between 2 and 8 hours before examination
Is one or both of your contact lenses lost or broken? (157)
damaged or lost lens
Do you want a new pair of contact lenses? (158)
wants replacement
No
Have you ever worn glasses to see better? (159)
No
worn glasses in the past
Are your glasses lost or broken? (160)
No
lost or broken
Are your frames broken? (161)
broken frames
R
R
R
R


R
R
R
R
Are your frames loose or uncomfortable?
(162)
frames need adjustment
Are your frames more than 2 years old?
(163)
frames more than 2 years old
Do you want new frames?
(164)
wants new frames
Are one or both of your lenses broken?
(165)
broken lens
Did you stop wearing your glasses for some reason other than they are lost or broken?
(166)
quit wearing Rx for some reason
Are your glasses less than a year old?
(167)
Rx less than one year old
Does patient wear contact lenses?
Yes
Do you want to start wearing contact lenses?
(168)
wants to wear contact lenses
Have you had good comfortable vision through your glasses in the past?
(169)
Rx unsatisfactory in the past
Have you good comfortable vision through your glasses now?
(170)
Rx unsatisfactory now
S
S


S
S
No
Do you want spare glasses or special purpose glasses?
(171)
wants additional pair of glasses
Do you want a spare pair of general wear glasses?
(172)
additional pair of general glasses
Do you want sunglasses?
(173)
sunglasses
Do you want reading glasses?
(174)
reading glasses
Do you want safety glasses?
(175)
safety glasses
Have you any hobbies or a job that requires special glasses?
(176)
occupational glasses
Are you in good health?
(177)
patient is in poor health
No
Is patient less than 23 yr old or more than 35 yr old?
Yes
Was your last eye examination less than one year ago?
(178)
last eye examination more than a year ago
Was your last eye examination less than three years ago?
(179)
last examination more than 3 years ago
Was your last physical examination less than one year ago?
(180)
T


1
last physical more than one year ago
Have you ever had a serious accident or illness?
(181)
serious accident or illness
Do you get car or sea sick?
(182)
motion sickness
Do you cover or close one eye to look at something closely?
(183)
uses one eye to look at something closely
Have these questions covered the reason you came in?
(184)
complaint not covered by questions asked
(Re-ask all questions answered "Don't know" first time through)



Sample Flow Chart: Final Cylindrical Axis, Cross Cylinder

Appendix II
SOME EXAMPLES OF
EYE TEST FLOW CHARTS FOR REFRACTOR III

Refractor III Subroutines

Tape Recorder Messages	Final Cylindrical Axis, Cross Cylinder
Notation	Sphere Power Check
Testing Sequence	Binocular Balance
Visual Acuity	Astigmatic Test Interaction
Interim Results	Effectivity Program
Approximate Spherical Correction	Near Add by NRA and PRA
Sequential Spherical Correction	Horizontal Phoria (by disassociation)
Check Degree of Fog	Horizontal Phoria
Cylindrical Axis, Astigmatic Line	Vertical Phoria
Approximate Cylindrical Axis, Cross Cylinder	Horizontal Ductions
Cylindrical Power, Cross Cylinder	Vertical Ductions

Tape Recorder Commands and Messages

Long Messages

1. Please move forward so that your head is against the headrest

2. When you hear this tone again, press the button that corresponds to the opening of the C. If you are not sure, make a guess. If you want to hear the instructions again, press the center button

3. If any set of lines is darker or sharper than any other, press the button that corresponds to that set of lines. If the lines are the same, press the center button

4. Which section has the clearer and sharper letters, the red section or the green section? At the sound of the tone, if the letters in the red section are sharper, press the top button. If the letters in the green section are sharper, press the bottom button. Press the right button if they are the same. If you want to hear the instructions again, press the center button

5. This is the end of the test. Thank you for your cooperation

6. Which lens makes the smallest letters you can see without squinting clearer, lens No. 1 or lens No. 2? Press the top button if No. 1 is clearer. Press the bottom button if No. 2 is clearer. Press the right button if they are the same. If you want to see the choices again, press the left button. If you want to hear the instructions again, press the center button

7. Look carefully at the smallest letters you can see without squinting. At the sound of the tone, press the top button if the letters are clear. Press the bottom button if the letters are blurred. If you want to hear the instructions again, press the center button

8. Which lines are darker and sharper, the horizontal lines or the vertical lines? At the sound of the tone, press the top button if the horizontal lines are sharper or press the bottom button if the vertical lines are sharper. Press the right button if they are the same. If you want to hear the instructions again, press the center button

9. If you see a flashing red bar above the white spot, press the top button. If the red bar is below the white spot, press the bottom button. If the red bar touches or crosses the white spot, press the right button. If you do not see a flashing red bar, press the left button. If you want to hear the instructions again, press the center button

10. If you see a flashing red bar to the left of the white spot, press the left button. If the red bar is to the right of the white spot, press the right button. If the red bar touches or crosses the white spot, press the top button. If you do not see a flashing red bar, press the bottom button. If you want to hear the instructions again, press the center button

11. When you see a single target or two targets that are so close together that you can combine them into a single target, press the top button. If you cannot make the two targets combine into a single target, press the bottom button. If you want to hear the instructions again, press the center button

12. You will see two targets, one above the other. If the top target is to the right of the bottom target, press the right button. If the top target is to the left of the bottom target, press the left button. If the top target is directly above the bottom target, press the bottom button. If you want to hear the instructions again, press the center button

Short Messages

1. Number 1	3. Left eye now	5. Number 2	7. Same choice again
2. Good	4. Please respond	6. Very good	8. Hello

Symbols

AO = Add, None
AE = Add, Empirical
AF = Add, Final
AT = Add, Tentative
Beep = Signal for Patient Response
BIC = Bichrome Letter Chart
BIP = Bipartite Letter Chart
BL = Bipartite Lens: -0.25 DS Left
+0.25 DS Right
BVA = Best Visual Acuity
CPA = Cylindrical Power, Approximate
CPAN = Cylindrical Power, Approximate New
CPF = Cylindrical Power, Final
CPT = Cylindrical Power, Temporary
C = Combined With
CX = Consecutive Circuits through a Loop
D = Counter
E = Error
EQ = Equal
FA = Approximate RX (between subroutines) defined as SPA + CPA + XA
FOG = FA with enough Plus Sphere Power to Fog (blur) Vision to 20/40 VA
FT = Temporary RX (within subroutines) defined as SPT + CPT + XT
G = Counter
H = Halt
K = Counter
L = Left
LC = Letter Chart
LM = Long Message
M = Multiplication Factor
N = No
NA = No Astigmatism
NLC = Near Letter Chart
NOAX = No Axis
NOR = No Objective Results
NRA = Negative Relative Accommodation
NS = Near Screen
OD = Right Eye
OR = Objective Results
ORR = Objective Results Retinoscope
ORX = Old RX
ORV = Objective Result, Visual Evoked Response
OS = Left Eye
OU = Both Eyes
PF = Power Factor
PRA = Positive Relative Accommodation
Q = Reaction Time as determined by Threshold VA Reaction Time
R = Right
RTL = Reaction Time Limit
RX = Prescription Powers and Axis
RRX = Recommended RX
SD = Snellen Denominator
SM = Short Message
SP = Spectacle Plane
SPA = Spherical Power Approximate (between subroutines)
SPT = Spherical Power Temporary (within a subroutine)
SPF = Spherical Power Final
SN = Slide Number
V = Clearest Line which the Patient Observes
VA = Visual Acuity
VAAE = Visual Acuity with Empirical Add
VAAF = Visual Acuity with Final Add
VAAO = Visual Acuity with No Add
VANOR = Visual Acuity, No Objective Results
VAORR = Visual Acuity, with Retinoscopy RX
VAORX = Visual Acuity, with Old RX
VAORV = Visual Acuity, with VEP RX
VEP = Visual Evoked Potential
W = Wrong
WPF = Write to Patient's File
X = Circuits through a Loop
XA = Cylindrical Axis, Approximate (between subroutines)
XAN = Cylindrical Axis, New
XC = Cross Cylinder
XC1 = Cross Cylinder No. 1
XC2 = Cross Cylinder No. 2
XF = Cylindrical Axis, Final
XT = Cylindrical Axis, Temporary
Y = Yes
Z = Counter

Sample Flow Chart: Cylindrical Axis Assessment Test

Axis of astigmatism as measured in degrees counterclockwise [illegible]

Slide No.	Left	SN	Right	SN	Top	SN	Bottom	SN	Center EQ
1	135.0	4	45.0	2	90.0	3	[illegible]		NA
2	22.5	14	67.5	17	45.0	6	E		H
3	67.5	16	112.5	19	90.0	7	E		H
4	135.0	8	157.5	21	112.5	18	E		H
5	157.5	20	22.5	15	180.0	9	E		H
6	34.0	22	45.0	10	56.0	23	E		H
7	90.0	11	79.0	24	101.0	25	E		H
8	124.0	26	135.0	12	146.0	27	E		H
9	180.0	13	169.0	28	11.0	29	E		H
10	50.5		39.5		45.0		E		H
11	84.5		90.0		96.0		E		H
12	129.5		140.5		135.0		E		H
13	174.5		180.0		5.5		E		H
14	17.0		22.5		28.0		34.0		H
15	11.0		17.0		22.5		28.0		H
16	62.0		67.5		73.0		79.0		H
17	56.0		62.0		67.5		73.0		H
18	107.0		112.5		118.0		124.0		H
19	101.0		107.0		112.5		118.0		H
20	152.0		157.5		163.0		169.0		H
21	146.0		152.0		157.5		163.0		H
22	28.0		34.0		39.5		45.0		H
23	62.0		56.0		50.5		45.0		H
24	73.0		79.0		84.5		90.0		H
25	107.0		90.0		95.5		101.0		H
26	135.0		129.5		124.0		118.0		H
27	152.0		146.0		140.5		135.0		H
28	163.0		169.0		174.5		180.0		H
29	11.0		180.0		5.5		17.0		H

E = Error, Repeat previous slide
NA = No astigmatism, XA = NOAX
H = Halt subroutine, XA = axis underlined on last slide presented; if two values are underlined, XA = mean value
3 repeats = NA

SN = Go to slide number SN
V = the clearest line which the patient observes
EQ = all lines are equal
Middle orientations are underlined

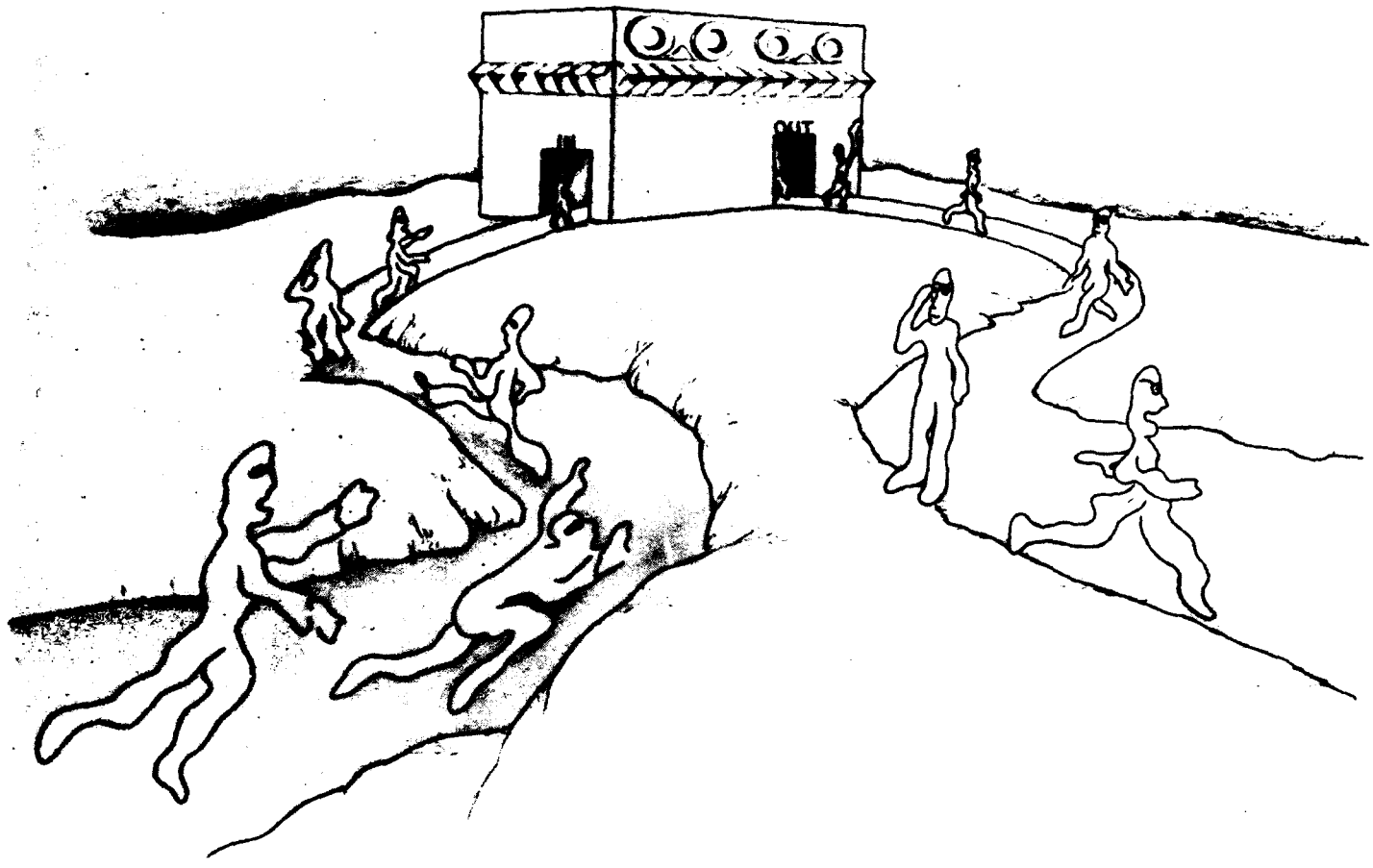


PLATE L. Ultimate successful automated eye examination

AUTHOR INDEX

SUBJECT INDEX

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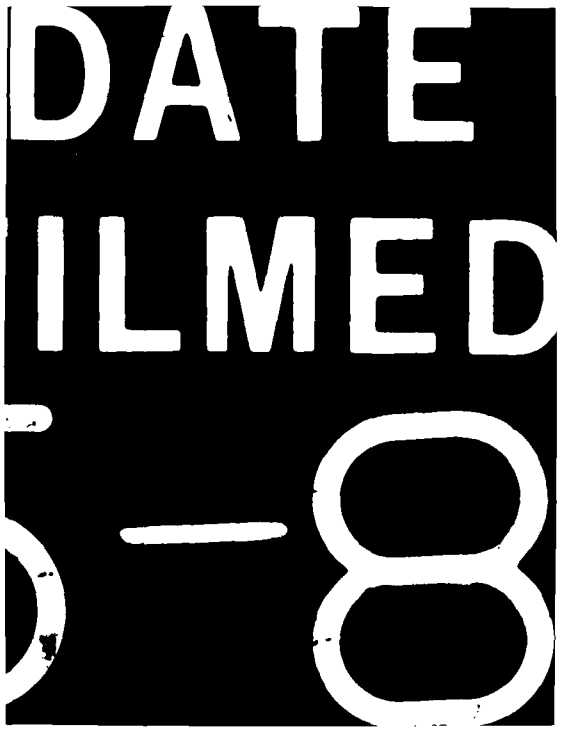
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